THE ELEMENTS OF ASTRONOMY

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A NON-MATHEMATICAL TEXTBOOK FOR USE AS AN INTRODUCTION TO THE SUBJECT IN COLLEGES, UNIVERSITIES, ETC., AND FOR THE GENERAL READER

BY

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PREFACE

This book is the result of attempting to present the subject-matter of astronomy to a number of classes of college students, over half of whom had had no mathematics beyond one year of algebra and one year of plane geometry in high school. In consequence, very little is presented in mathematical form, but an effort has been made to develop the necessary physical concepts so that at the close of the course the student would be in possession of the main facts of the subject as well as have an elementary understanding of the principles and methods involved in modern astronomical investigation.

An effort was made to have the material represent the state of the science at the end of 1925, to the extent that it was available in publications accessible to the author. Much interesting material was of necessity omitted in order to avoid too lengthy a treatment in a first course. It is hoped, however, that no important results have been omitted.

The increasing use of the metric system has led the author to believe that the time has come to adopt it in a textbook of this character. The equivalents in the English system of units are given in parentheses after the metric values for those who do not care to make the change of systems.

Whenever possible, credit was given to the one originating an idea or beginning a new line of investigation. In many cases, however, it seemed impossible to trace matters to their sources, as so much is now common knowledge and the names of originators appear to be lost.

The author is under great obligation and hereby expresses his sincere thanks to many who have aided him in the preparation of this book. He is especially indebted to Prof. E. B. Frost for the use of the facilities of the library of the Yerkes Observatory during the summer of 1925; to his colleague, Prof. C. H. Gingrich of Carleton College, who read the entire manuscript and proof; to Prof. S. Einarsson, of the University of California, who read a portion of the manuscript and to Prof. W. F. G. Swann of Yale University for the statement of the Einstein theory of relativity

in Sec. 140. Permission to use photographic material or drawings was freely given by many. Without these fine results of modern observing the value of the book would have been greatly impaired. The source of each illustration thus obtained is given in the appropriate place.

Every effort was made to avoid errors in the manuscript, but as it is impossible to avoid all mistakes the author will appreciate having any such called to his attention, no matter how unimportant.

This book is offered by the writer to such of his fellow-teachers as care to use it, with the hope that it may be of some use in presenting the elementary facts of our great science in a form that the first-year student can comprehend. It is also offered to the general reader who may desire to have a non-mathematical treatment of the science of the stars, with the wish that it may afford him both pleasure and profit.

THE AUTHOR.

GOODSELL OBSERVATORY,
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May, 1926.

CONTENTS

THE ELEMENTS OF ASTRONOMY

CHAPTER I

INTRODUCTION

Astronomy is the science of the heavenly bodies. These include the sun, moon, planets and satellites, comets, stars and nebulæ. The pursuit of astronomy implies not only a study of these bodies with relation to their distances, dimensions, movements, physical characteristics and the laws which govern them, but also the attempt to determine both their past and future.

1. Early Astronomy.—When man was nothing more than a savage it was necessary for him to pay some attention to astronomical occurrences, even if only to the extent of recognizing the daily return of the sun or the connection between the growth of vegetation and the seasons.

At a later stage of development he used the day, month and year as units of time, and many religious observances were timed by the position of sun or moon in the sky. There is some evidence that at least certain of the Egyptian pyramids were used in making astronomical observations and ancient temples and other places of worship were frequently oriented with respect to sun or stars.

So far as can be determined, astronomy was the first of the sciences to be developed by the ancients, and its study, without doubt, played an important part in the intellectual development of ancient peoples. Old records of the Chinese, writings on Babylonian tablets and remnants from the chronicles of the early Egyptians all show evidence of the cultivation of astronomy. They contain records of eclipses of sun and moon, the appearance of bright comets, the conjunctions of planets, etc.

Ancient navigators used the stars to guide them when they made their voyages, caravans across the deserts did likewise and the old-time shepherd or farmer was aided in his pursuits by paying attention to sun and stars.

2. Place of Astronomy among the Sciences.—Astronomy is the only one of the sciences which gives man some knowledge of the entire visible universe. Other sciences devote their attention to some one phase of the universe and play their part in getting an understanding of some of the fundamental laws governing matter and energy, but they restrict themselves, almost exclusively, to those phases of nature which are in evidence upon the earth, which is only an insignificant part of the whole. Astronomy, however, strives to unravel the secrets of nature, not only upon the earth but also throughout all space within reach of the most powerful instruments, and thus acquaints man with his immediate surroundings as well as with what is going on in regions far removed from ordinary, everyday experience and contacts. One of the goals of astronomy may be said to be to make man feel "at home" in the universe.

3. Relation of Astronomy to Other Sciences.—In pursuing as its aim the understanding of the universe, astronomy is indebted to other sciences for much of its progress. It utilizes the information gathered by the students of physics, chemistry, geology and biology as well as all the resources of mathematics. It repays the debt by unfolding to these sciences the vast laboratories in sun, stars and nebulæ, where matter is met with in a variety of forms and under conditions which cannot as yet be duplicated on the earth.

The solution of some astronomical problems has been the direct cause of some of the greatest developments in mathematics. Newton's "Principia" stands as one of the greatest products of the human intellect, and it was the desire to solve the problem of the motions of the members of the solar system which led its author to produce it.

4. Practical Aspects of Astronomy.—Accurate time, land surveys, international boundaries, map making or cartography, and navigation are directly dependent upon astronomical observations.

Accurate time is one of the necessities of modern civilization. The astronomer sets his clocks by means of observations of the stars, and the official time of all civilized countries is obtained from the clocks in the astronomical observatories.

Land surveys depend upon a knowledge of true north-and-south lines. These are determined by astronomical observations and are the prime meridians upon which accurate surveys depend.

When the 49th parallel of latitude was decided upon as part of the boundary line between the United States and Canada the international commission appointed to mark this line included eminent astronomers from both countries, by whose observations of the stars the exact location was determined.

Map making depends upon an exact knowledge of the shape and the size of the earth and the locations of the meridians and parallels. This knowledge is directly dependent upon observations of the stars whose exact positions in the heavens have been determined by generations of astronomers.

The location of a ship at sea is obtained by astronomical observations and the deviations of the compass are found by comparing it with known directions in the sky. Without such knowledge modern commerce would be greatly handicapped and it is doubtful if it could be carried on successfully if this information were lacking.

It is thus evident that the modern world is greatly indebted to astronomy, which supplies it with time, directions, positions on the earth and their relationships.

Another phase of astronomy is being developed at the present time which presages vast possibilities of service to mankind. The weather and the climate of any region on the earth are largely dependent, in the last analysis, upon the heat which comes from the sun. A careful study of the heat received from this body shows that the amount undergoes minute changes from day to day and larger variations in longer periods of time. A correlation has been shown to exist between the amount of heat received at any time and the mean temperatures, several days later, at certain selected stations. This correlation is so close that it is used to forecast temperatures with considerable success. It seems possible, therefore, that in time such forecasts can be made for any place on the earth. It also seems possible that the law of variation of the sun's heat will ultimately be discovered and the heat to be received in a month or a year thus rendered capable of prediction in advance. When this shall be accomplished, long-range weather forecasts will almost certainly follow. The immense value to agriculture of the previous knowledge that a certain summer will be hot, cold, wet or dry can hardly be overestimated if the world's food supply continues to come from the land. Such a development of astronomy is as yet little more than a dream, but it does not seem wholly outside the realm of possibility.

5. Place of Astronomy in Education.—The greatest value of astronomy to the average individual at the present time lies in its appeal to the intellect. The contemplation of great worlds outside the earth; the study of the stars individually, in clusters or in vast systems; the realization that the universe is a universe of order and subject to law; the gradual discovery of the laws in accordance with which it operates and the thoughts aroused as to its origin, purpose and future development will more than repay the investment of time and effort necessary to make them possible.

To the great majority the universe is practically a sealed book. We exert ourselves through great educational systems, maintained at enormous expense, to make the student acquainted with his city, state and nation as well as with foreign lands, and we endeavor to acquaint him with the laws of nature as they operate on this small earth, so that he shall feel in touch with his environment, but, thus far, we have done very little to make him acquainted with the vast universe in which he finds himself, and we allow him to spend his entire life in ignorance of the wonderful realms outside the earth. It is important that he be acquainted with the earth and what it contains, but it seems a great mistake to keep his thoughts forever centered on this globe and not allow them to go out to the stars.

6. Subdivisions of Astronomy.—According to purpose and method, astronomy may be divided into four main branches: astrometry, practical astronomy, theoretical astronomy and astrophysics.

Astrometry deals primarily with the measurement of the positions, distances, dimensions and apparent motions of the heavenly bodies; *practical astronomy* deals with such matters as the determination of time, latitude and longitude; *theoretical astronomy* devotes itself to the mathematical study of the motions of the heavenly bodies under the influence of gravitation; and *astrophysics* deals with their physical and chemical characteristics, such as brightness, temperature, composition, magnetic properties, motion in the line of sight as determined by the spectrograph, etc. There is, however, no sharp distinction between these various parts of the subject, each being more or less connected with or dependent upon the others.

CHAPTER II

THE EARTH

All astronomical observations must be made at the earth's surface and through the earth's atmosphere. These circumstances determine, to a large extent, not only what we can learn concerning the heavens, but also the methods which must be employed in studying them. It is therefore necessary to learn something about the earth before we can study the rest of the universe to the best advantage.

7. Facts Concerning the Earth.—The following facts may be stated concerning the earth, and then each one will be examined more in detail:

1. The earth is an oblate spheroid having a polar diameter of 12,714 km (7900 miles) and an equatorial diameter of 12,757 km (7927 miles). The mean diameter is 12,742 km (7918 miles).

2. Its mass is equal to 5.5×10^{21} metric tons (6×10^{21} English tons) and its mean density is about 5.5 times that of water.

3. The earth rotates on its axis once in 24 sidereal hours in a direction from west to east.

4. The earth revolves about the sun at a mean distance of 149,504,000 km (92,897,000 miles) once a year. This revolution is from west to east. Its orbital velocity is about 30 km (18.5 miles) per second.

8. The Earth's Shape.—Mankind, with few exceptions, seems always to have held the belief that the earth is approximately flat, and it was not until Magellan's ships actually sailed around it that the age-long belief was shattered and the rotundity of the earth accepted as a fact.

Another of the elementary proofs that the earth is at least approximately spherical can be obtained by observing eclipses of the moon. No matter how the moon moves into or out of the shadow of the earth, the edge of the shadow is always seen to be bounded by an arc of a circle (Fig. 1).

Another proof of its approximate shape is that when a vessel is observed going out to sea the hull vanishes first, the superstructure next and the smoke from its fires last.

FIG. 1.—Partial phases of a lunar eclipse showing boundary of earth's shadow to be an arc of a circle. (*Photographed by Barnard of the Yerkes Observatory.*)

9. The Earth's Dimensions.—The exact dimensions of the earth are obtained by measurement. The process is termed *triangulation* because it depends upon a network of triangles, and is indicated in principle in Fig. 2.

Suppose it is desired to determine the distance between two points, A and G, so far apart that one can not be seen from the other nor both from a single intermediate point. First a distance AC is measured with great exactness. This is termed a base-line. Then, after selecting a point B, the angles A, C and B in the triangle are measured by a surveyor's transit or similar instrument. In the triangle ACB one side, AC, and the three angles are known, so that the other two sides can be computed by trigonometry. Another point, E, is then selected which is visible from B and C. Having computed CB and measured the angles at C, B and E in the triangle CBE, it is, in turn, possible to compute the length EB. This process is continued until the final triangle EFG is solved. In the triangle CEG we now know CE, EG and the angle CEG so that CG can be computed. Then in the triangle CGA we know CG, CA and the angle ACG, so that we are in a position to compute AG, the distance required.

In this statement it has been assumed that all the triangles lie in the same plane. Because of the curvature of the earth's surface it is evident that this is not actually the case, although

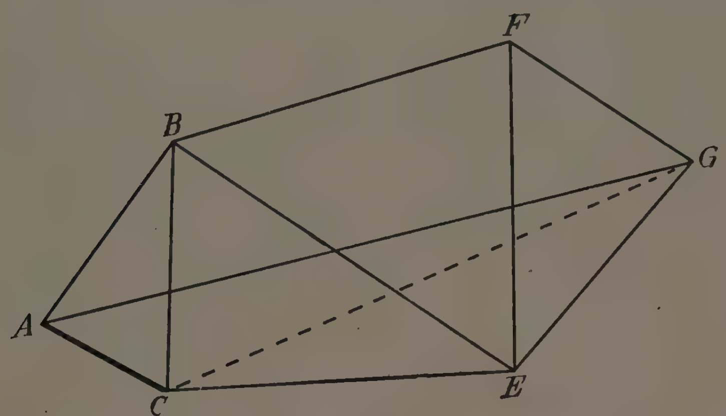


FIG. 2.—The principle of determining the distance between two points, A and G, by triangulation.

each triangle is in itself a plane triangle. This complicates the problem, but the principle used is the same.

Many such lines have been measured in this manner in various countries. It is evident that such a network of lines of known length, used in connection with the known longitudes and latitudes of the places connected, enables us to know the dimensions of the earth with great accuracy.

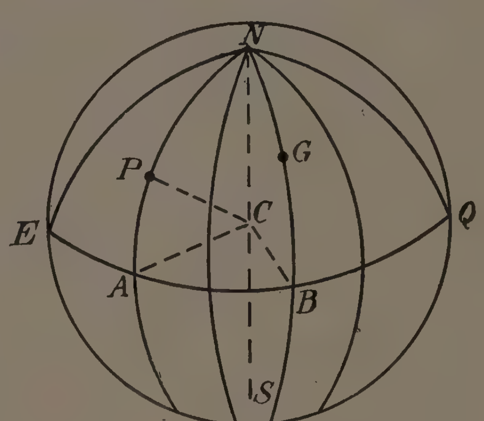


FIG. 3.

10. Longitude.—From a study of geography we are familiar with the terms *longitude* and *latitude.* We say that if we assume a series of imaginary lines, meridians, drawn from the north to the south pole of the earth (Fig. 3), and designate a certain meridian, such as NGS, as the zero meridian, then the longitude of a point P is the angle which the meridian through P makes with this zero meridian, namely, the angle PNG. We also know from the geometry of the problem that the angle PNG is equal to the angle ACB subtended at the center of the earth by that part of the equator between the two meridians. Longitude is measured east and west from the meridian through Greenwich, England.

11. Plumb-lines and Level Lines.—If a plumb-line is hanging freely, its direction with respect to the earth is determined by the

direction of gravity. The direction of the plumb-line is usually determined by first leveling an instrument by means of delicate spirit levels and then turning off an angle of 90° in a vertical plane. A level surface is perpendicular to the direction of the plumb-line at any point.

If the surface of the ocean were not disturbed by waves and tides it would be a level surface. A level surface therefore is not a plane but a curved surface. Similarly, a level line is not a straight line but a curved line which follows the curvature of a level surface.

12. Latitude.—There are three kinds of latitude: astronomical, geographic and geocentric.

1. *Astronomical latitude* is defined as the angle between the direction of the plumb-line and the plane of the earth's equator. If the earth were a homogeneous sphere without rotation the plumb-line would point toward its center, but, as we shall see later on, the earth is not an exact sphere and it is evident to everyone that matter is not uniformly distributed at the surface at any rate, for in some places we have a water surface and in others there are mountains. This lack of uniformity in the distribution of matter at the earth's surface, as well as any lack of uniformity within the body of the earth, will make the direction of the plumb-line slightly different on the rotating earth from what it would be if these inequalities of surface, etc. were not present. This effect on the plumb-line is called the *station error*. In Hawaii station errors up to 67″ have been noted. The method of determining station error is somewhat beyond the scope of this book.

2. *Geographic latitude* is the astronomical latitude corrected for station error. It is the latitude used in the drawing of maps.

3. *Geocentric latitude* is the angle at the center of the earth between the line drawn from the center to the point on the surface and the plane of the equator. Thus, in Fig. 3 the angle PCA is the geocentric latitude of the point P.

The greatest difference between geographic and geocentric latitude occurs at 45°, where it amounts to 11′.6. Geocentric latitude is used when results calculated for the earth's center must be changed to a point of observation at the surface, and *vice versa*.

13. Length of a Degree of Latitude.—In traveling along a meridian from the equator toward a pole it is found that it is

necessary to travel a little further for each change of 1° in latitude. This means that the curvature of the earth's surface is greatest at the equator and that it becomes less the nearer we approach the poles. This is illustrated in Fig. 4. Each line drawn toward the interior is perpendicular to the tangent at the point of the curve from which it is drawn, and is therefore the direction of the plumb-line at the surface. The angles between adjacent lines are all equal. It is therefore evident that the arc of the meridian between adjacent lines at the pole is greater than at the equator, or that a degree of latitude increases in length as one goes away from the equator. Measurements of arcs of meridians in various

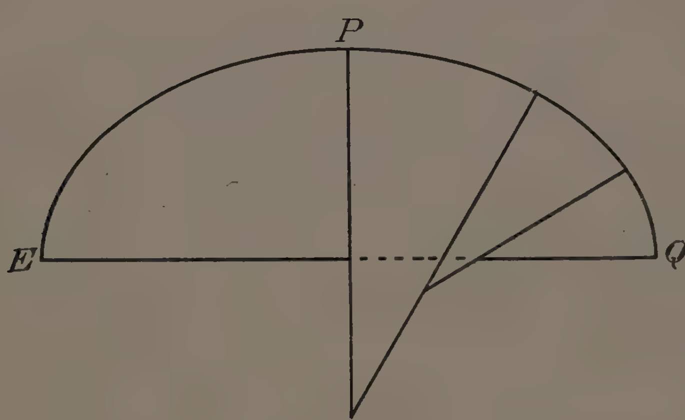


FIG. 4.

parts of the earth have shown the following values for the length of 1° of astronomical latitude:

	KILOMETERS	MILES
At equator	110.55	68.71
At 45°	111.12	69.06
At 90°	111.68	69.41

Arcs of longitude along parallels have also been measured, and it is found that these are essentially uniformly curved at any particular latitude.

From these results we reach the conclusion that the earth becomes flatter the nearer we approach the poles, so that the actual shape of the earth is that of an oblate spheroid with a polar radius of 6356.91 km (3949.99 miles) and an equatorial radius of 6378.39 km (3963.34 miles).

14. The Variation of Latitude and Longitude.—Many years ago the question was raised whether the possible shifting of

masses within the earth, the denudation of the continents and even seasonal changes might not produce a sufficient change in the position of matter within or on the earth to have an appreciable effect on the position of the axis of rotation with respect to the body of the earth. This change in the axis of rotation would show itself in changes in the latitudes and longitudes of places on the earth.

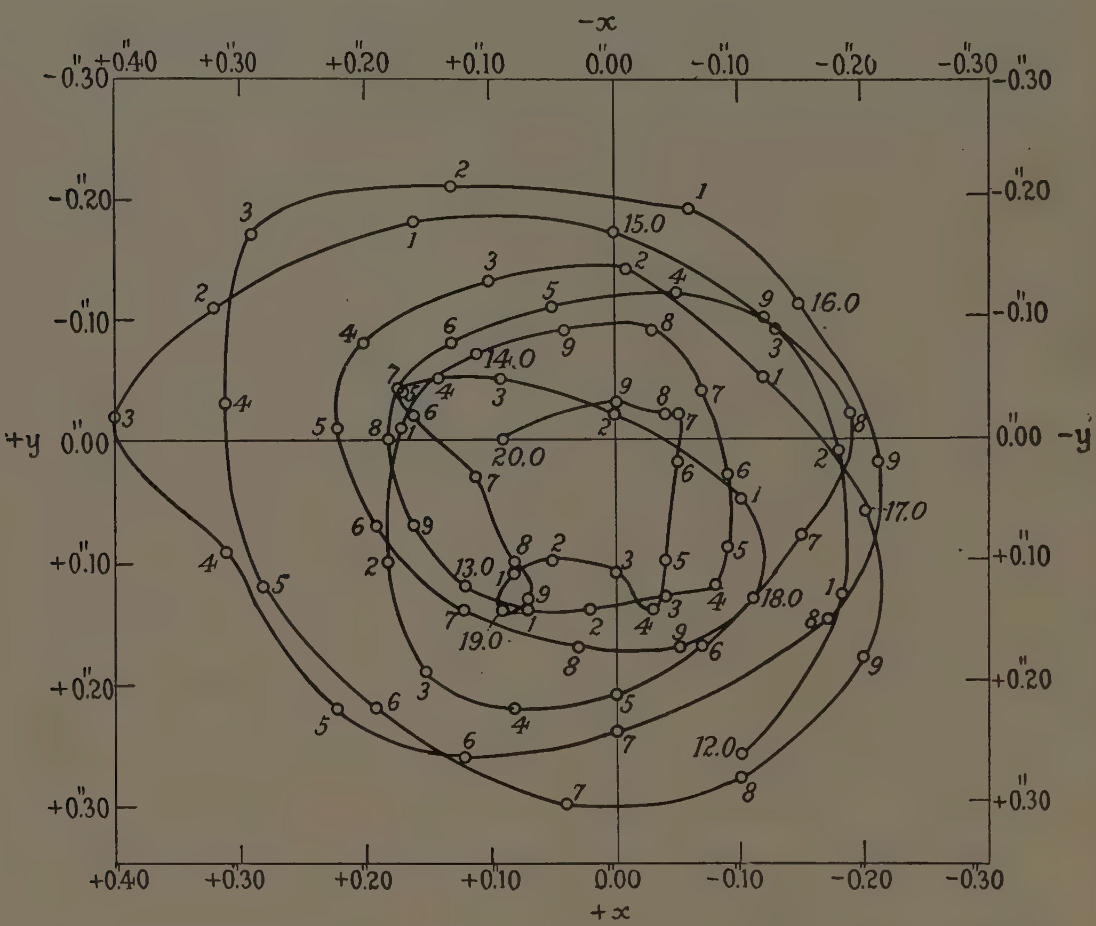


FIG. 5.—The motion of the north pole of the earth from 1912 to 1920. (*According to Wanach.*)

In 1888, Küstner published a series of observations made in 1884 and 1885 at Berlin, in which he showed that variation in the latitude of the Berlin Observatory had occurred in the course of the observations. During the same period Chandler at Cambridge, Mass., had shown that a variation existed in the measures of the latitude of the Harvard Observatory. Küstner's results led to special test observations at Berlin, Potsdam, Prague and Strassburg in 1889, which showed such accordant results that the problem was attacked by the International Geodetic Institute

and for a long series of years observations were made at selected stations, mostly in the northern hemisphere. Some of these stations are still in operation. The results obtained show clearly that the rotation axis is not fixed with respect to the earth but is moving about a mean position. Another way of expressing this fact is to say that the poles wander about within a small area on the surface of the earth. Figure 5 shows the motion of the north pole of the earth from 1912 to 1920. The figure is taken from the report of Wanach in *Astronomische Nachrichten*.

It is evident that if the poles change their positions the meridians which join the poles must also be in motion. In consequence, there will be slight changes in the longitudes of places on the earth as well as changes in the latitudes.

15. The Mass of the Earth.—The *mass* of a body is usually defined as the amount of matter it contains. The word "mass" must not be confused with the word "weight." The weight of a body is a measure of the gravitational effect of the earth upon the mass of the body and this varies inversely as the square of the distance of the body from the center of the earth. Thus a mass of 1 kg would weigh 1 kg at the earth's surface, but if the weighing took place at a point whose distance from the earth's center is equal to two radii of the earth its weight would be but ¼ kg if a spring balance were used. The amount of matter in the object, however, is the same—1 kg.

The first attempt to determine the mass of the earth was made by the English astronomer, Maskelyne, in 1774. His method was the following:

In Scotland there is a mountain Schehallien. By observing the direction of the vertical (plumb-line) on either side of the mountain (Fig. 6) it was possible to determine how much the mass of the mountain deflected the plumb-line. By surveys and borings it was possible to determine the mass of the mountain. Then, knowing the distance to the center of mass of the mountain and the distance to the center of the earth, it was possible to compare the gravitative effect of the earth with that of the mountain and thus determine the mass of the earth.

The modern method of the torsion pendulum, while somewhat similar in principle, is capable of producing far more accurate results and is therefore more reliable than the mountain method. A light rod is suspended horizontally by means of a fine fiber and a small ball of some heavy substance like gold or platinum is

fastened to each end of the rod. If the apparatus is carefully shielded from air currents or placed in a vacuum it will gradually come to rest in such a position that there will be no twist in the fiber. If we then rotate the rod slightly about the fiber, the twist produced in the fiber will cause the rod to vibrate slowly. If we know the mass of the balls and rod, the length of the rod and the

FIG. 6.—The mountain method of determining the mass of the earth.

time of vibration we can determine the force necessary to twist the fiber through any angle. The formula

$$T = 2\pi\sqrt{\frac{k}{f}}$$

gives the time of one complete vibration in terms of the force f with which the fiber resists being twisted, and a constant k which involves the length of the rod, its mass and the mass of the small balls. Since we can measure the quantities involved in k and can time the vibration, the formula enables us to determine f, the force required to twist the fiber through unit angle. It will be noted that this formula is very similar to that used for simple pendulums, $T = 2\pi\sqrt{\frac{l}{g}}$.

If the torsion pendulum is allowed to come to rest and then two large balls of lead or other heavy substance are brought into positions B, these large balls will attract the small ones and the latter will move until the twisting of the fiber prevents further movement (Fig. 7). If we then measure the angle through which the rod has turned and the distance d between the centers of the large and small balls we have, by means of the equation given above, a direct measure of the attraction of b for B at distance d.

The attraction of the earth for the ball b is measured by its weight when corrected for the centrifugal effect of the earth's

rotation at the point where the observations are made. We can then write

$$w = \frac{k' \times b \times E}{R^2} \text{ or } b = \frac{w \times R^2}{k' \times E},$$

where k' is a constant depending on the units used, b the mass of

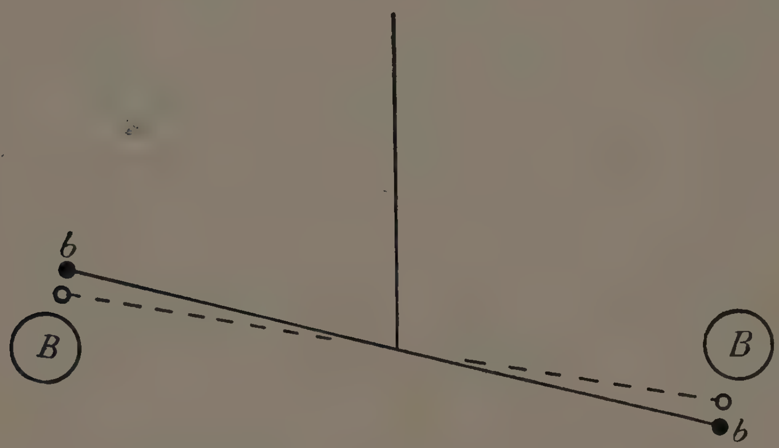


FIG. 7.—The torsion pendulum as used to determine the mass of the earth.

the small ball, w the weight of the small ball, E the mass of the earth and R the earth's radius.

Similarly, we can write

$$f' = \frac{k' \times b \times B}{d^2} \text{ or } b = \frac{f' \times d^2}{k' \times B}.$$

Equating these two values of b we obtain

$$\frac{w \times R^2}{k' \times E} = \frac{f' \times d^2}{k' \times B}.$$

Solving this equation for E, we have

$$E = B \times \frac{w}{f'} \times \frac{R^2}{d^2},$$

which gives the mass of the earth in terms of the mass of B.

Other methods involving delicate balances or pendulums have also been devised, all yielding approximately the same values for the earth's mass.

The mass of the earth determined in some such manner comes out to be equivalent to 5.5×10^{21} metric tons of mass, or 6×10^{21} English tons.

16. The Earth's Density.—After having determined the mass of the earth by the methods of Sec. 15 and the volume of the

earth from the dimensions given in Sec. 13 we are in a position to obtain the mean density of the earth. Applying the well-known equation in physics, $D = \frac{M}{V}$, where D is the density, M the mass and V the volume expressed in the proper units, we obtain the mean density of the earth. The mean value derived from various determinations is about 5.5 times the density of water.

Since the density of rocks near the surface of the earth is seldom over 2.75, it is evident that the material near the center must have a density considerably greater than the mean density in order to produce an average of 5.5. It is thought by many that the central parts of the earth are either composed almost wholly of iron or are at least very rich in iron and heavy elements.

17. Rotation.—The earth's rotation may be proved in a number of ways. We shall consider two of them, the Foucault pendulum and the change in the value of gravity as we go from pole to equator.

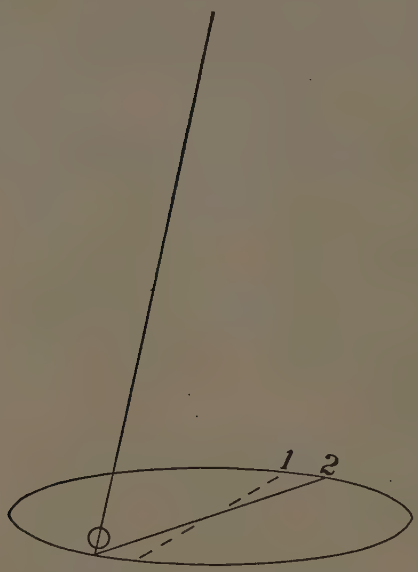


FIG. 8.—The Foucault-pendulum method of showing the rotation of the earth.

The first of these was performed by the French physicist, Foucault, in 1851. He suspended a heavy iron ball about 30 cm (1 foot) in diameter by means of a wire about 60 meters (200 feet) in length. After the pendulum had been drawn aside and allowed to come to rest it was started swinging and a pin fastened to the bottom of the iron ball was allowed to cut a ring of sand. It soon became evident that the plane in which the pendulum vibrated deviated toward the right with reference to the floor, that is, in reality the floor was turning under the pendulum, or the earth was rotating. Figure 8 illustrates this.

It is evident that if a pendulum which is free to move in any direction could be set up at the pole, the earth would turn around under it once in 24 hours. At the equator, on the other hand, the plane of the pendulum would continuously cut the earth's surface at the same angle and no shift would occur. In intermediate latitudes, therefore, the time of rotation would increase from 24 hours at the pole to an infinitely long time at the equator.

In latitude 45° the rate of rotation would be one complete rotation of the plane of the pendulum in about 34 hours.

The experiment has been repeated many times since Foucault's day. In order to be successful, great care must be taken to see that the support is so designed that the pendulum is actually free to move in any direction, that the ball is smooth and symmetrical with respect to the wire and that it is at rest before starting to swing. A recently designed pendulum only 3 meters (10 feet) long has proved successful.

The second proof depends upon the fact that the force of gravity at the equator is less than at the poles. After allowing for the decrease in the force caused by the equatorial radius being 21.5 km (13.4 miles) greater than the polar radius, it is found that there is a difference which is exactly equal to the effect of the centrifugal force developed by the earth's rotation. This experiment is performed by means of a specially devised pendulum. It will be remembered that the vibration time of a pendulum is given by the equation

$$T = 2\pi\sqrt{\frac{l}{g}},$$

where l is the length of the pendulum and g is the force of gravity. By timing the swing of the pendulum the only unknown in the equation is g, and the value of this can therefore be determined wherever the pendulum can be set up and the means of accurate timing are available.

Other proofs are the eastward deviation of falling bodies; the deviation of projectiles, which is toward the right in the northern hemisphere and toward the left in the southern; the trade winds and the direction of revolution of the winds in cyclones, which is counterclockwise in the northern hemisphere and clockwise in the southern.

The question of the constancy of the earth's rotation is of the greatest importance in astronomy, because the day is the fundamental unit of time. Various natural processes must affect the period of rotation. If the earth's diameter were shrinking, the period would decrease, while if expanding, it would increase, provided the mass remains constant. If meteoric matter is adding to the mass while other things remain unchanged the period must be increasing. The friction of the tides will act like a brake on the rotating earth and lengthen the period. Jeffreys estimates that the day has increased in length by 1 second in the

last 120,000 years because of tidal friction. It is clear that the problem is not easily solved, but, from the evidence available, it seems probable that the day has not changed in length by as much as 0.01 second during the Christian era.

18. The Diurnal Rotation of the Heavens.—If we stand in a room and slowly turn around we see that all the objects about us appear to be going around in a direction opposite to that in which we turn. We have a similar experience if we place ourselves on a rotating platform, such as a merry-go-round. In the first case we could also note, by looking directly upward, that the ceiling

Fig. 9.—Star trails around the north celestial pole. Exposure 11.5 hours. (*Photographed by Wilson at the Goodsell Observatory.*)

would appear to be turning about a point directly overhead, and, in the second case, we could see that the sky would appear to be turning about a point directly above the center of rotation of the merry-go-round. These points in ceiling or sky we shall call the rotation poles—they are the points where the axes around which our rotation takes place reach the boundary of our surroundings. We would also find a similar pole directly opposite the first around which floor or ground, respectively, would appear to rotate.

The earth is a globe rotating about an axis. If at night we observe the position of the stars for several hours we see that

there is a point in the sky about which the stars appear to turn. In the northern hemisphere this point will be above the north point of the horizon, and in the southern hemisphere it will be above the south point. These two points are called the north and south *celestial poles* and are the points where the earth's axis prolonged in opposite directions appears to pierce the sky. The stars near these poles appear to move around them in circles, and cameras with reasonably large lenses can be used to photograph them. Figure 9 is such a photograph, made at the Goodsell Observatory with an exposure of 11.5 hours, of the star trails around the north celestial pole. If the sky were clear and dark for 24 hours the trails would form complete circles.

The period of rotation with respect to the stars is 24 sidereal hours, or $23^h\ 56^m\ 4^s.1$ mean time.

The apparent rotation of the heavens may be considered another proof of the rotation of the earth.

19. Atmospheric Pressure.—The gases of the atmosphere are bound to the earth by its gravitation. The lowest layer must therefore support the weight of all other layers. In consequence, the air at sea-level is compressed most and is therefore densest, while the higher we go above sea-level the less air remains above, the pressure decreases and the density diminishes.

The instrument used to measure air pressure is the barometer. At sea-level the pressure is equal to 1100 grams per square centimeter (15 pounds per square inch) and will support a column of mercury 76 cm (30 inches) high. The barometric pressure diminishes about one-half for each 5.5 km (3.5 miles) of elevation, that is, the pressure at 5.5 km is 38 cm, at 11 km it is 19 cm, etc.

This decrease in pressure is accompanied by a corresponding decrease in density, since the density of a gas is directly proportional to its pressure provided the temperature remains constant. The density of the atmosphere at sea-level is approximately 0.0012 that of water.

20. The Height of the Atmosphere.—Theoretically, there is almost no limit to the height of the atmosphere but practically a limit can be found. On the basis of 50 per cent decrease in density for each 5.5-km elevation a brief calculation shows that at an elevation of 55 km the density has decreased to less than 0.001 of the density at sea-level and at 72 km the density is only about 0.0001. It is therefore evident that at no very great

elevation the density is less than that of the highest vacuum attainable in the laboratory.

A second method of determining a limit is by means of shooting stars. These are small particles, entering the atmosphere at high velocities, which are rendered incandescent by the friction of the air. Shooting stars seldom appear at heights exceeding 150 km (100 miles).

A third method is the determination of the height of the aurora, a luminosity of the upper atmosphere apparently caused by electric discharges from the sun (Sec. 163). Norwegian observers, especially Störmer, have made many observations on this point and they find only occasional streamers to exceed a height of 300 km. One of these reached a height of 750 km (470 miles). We may, therefore, take this value as the approximate limit of an appreciable atmosphere for the earth.

21. Astronomical Refraction.—When a ray of light passes from a rarer to a denser medium it is bent toward a line perpendicular to the surface separating them (Sec. 51). A ray of light

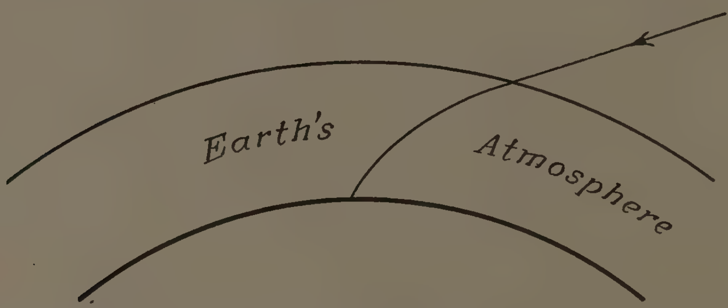


FIG. 10.—Refraction of a ray of starlight by the earth's atmosphere.

passing from the practically absolute vacuum of interstellar space into the earth's atmosphere suffers a similar deviation, and the deeper it penetrates the denser the air becomes, and hence the greater the deviation until it reaches the earth's surface. Figure 10 illustrates this, although the bending of the ray of light in the figure is greatly exaggerated. This bending of the ray is called *astronomical refraction.*

A ray which enters the atmosphere so as just to graze the earth's surface will be compelled to pass through the air at a larger angle of incidence than one coming in more nearly perpendicular to it, and in consequence the refraction is greater. On the other hand, a ray entering exactly perpendicularly is not affected at all. The refraction accordingly varies with the altitude of the source

of light above the horizon. At the horizon the refraction amounts to 35′; at an altitude of 10° it is reduced to 5′, at 45° to 1′ and at the zenith it becomes 0. These are mean values for average observing conditions. Refraction increases with increase in barometric pressure and decrease in temperature, and *vice versa.*

In consequence of refraction, a heavenly body is never exactly in the direction we see it unless in the zenith. When accurate observations for position are made it is necessary to correct these for refraction, and in observatories where such observations are made there are usually rather extensive tables already calculated, so that the corrections may be determined quickly.

The sun and moon have apparent diameters of about 32′ and 31′ respectively. When the lower edge of one of these bodies is just seen above the horizon that edge is in reality 35′ below the horizon, but refraction elevates it by that amount. Hence we see the entire body when its zenith distance is over 90° and therefore below the horizon plane.

When the sun is just rising or setting it often assumes an elliptical shape with the longer diameter parallel to the horizon. This is caused by the refraction raising the lower edge more than the upper and therefore apparently shortening the diameter perpendicular to the horizon.

22. Twinkling of the Stars.—On a hot summer day distant objects near the horizon appear to be trembling. Similar effects can be seen by looking at an object if the line of sight passes near a heated surface, such as a stove. This trembling is caused by the unequally heated air masses, which produce a varying refraction as they move across the line of vision.

In the earth's atmosphere there are found various air currents, the air of which is at different temperatures. At the boundary between any two currents there is a mixing of the two air masses, which thus gives rise to irregular motions in a beam of light coming from a star. This irregularity is called *twinkling* or *scintillation.*

The twinkling of a star in the telescope appears as a rapid motion of the image, and this motion is magnified by the eyepiece. The larger the telescope the greater the number of irregularities in the line of sight. On some perfectly clear nights large telescopes cannot be used because the image is too unsteady

to permit anything to be seen properly. Steadiness of the image is essential to good observing. The quality of the steadiness is usually termed the *seeing*.

23. The Earth's Orbit and Motion around the Sun.—If we observe the stars near the setting sun for a few weeks we shall see that they appear a little lower in the sky each evening. This shows that the sun is moving eastward among the stars. If we continue our observations for an entire year we shall find that at the end of the period the sun has made a complete circuit among the stars and is again at the starting point. This apparent motion of the sun is explained by the earth's revolution about it in a year.

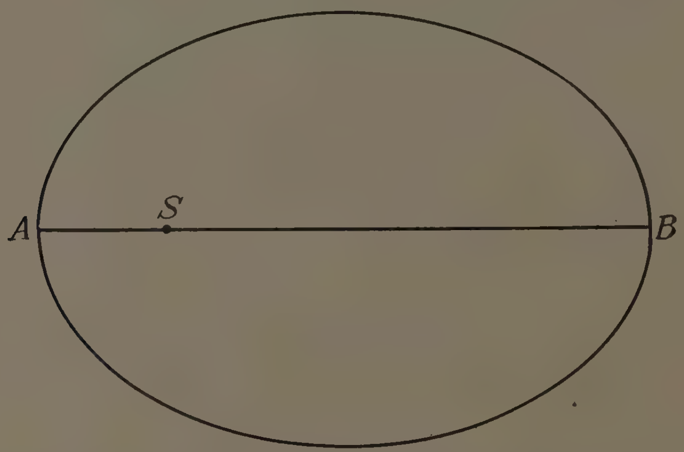


Fig. 11.—The general shape of the earth's orbit about the sun. The ellipticity is greatly exaggerated in the figure.

The apparent path of the sun among the stars is called the *ecliptic*. When marked on a celestial globe it proves to be a great circle. This means that the earth's path about the sun lies in a plane. The plane of the earth's orbit is termed the plane of the ecliptic.

The shape of the earth's orbit is that of an ellipse (Fig. 11), with the sun at one focus. The longest diameter of the ellipse is called the major axis. The point A of the orbit at the end of the major axis which is nearest the sun is called *perihelion* and the point B, farthest from the sun, is called *aphelion*.

The half-length of the major axis, or semi-major axis, is called the mean distance from earth to sun. It is very nearly 150,000,000 km (92,900,000 miles) in length.

As the earth's orbit is nearly circular, we may assume, without serious error, that its radius is equal to the semi-major axis.

Multiplying this length by 2π and dividing by the number of seconds in a year will give the velocity of the earth in its orbit. This amounts to 30 km (18.5 miles) per second approximately.

24. Aberration.—If rain is falling vertically, the drops will fall directly through a vertical tube, but if the tube is moved horizontally, it is necessary to tip the upper end forward in order to allow the drops to fall freely through the tube without striking the sides (Fig. 12). If the tube is moved in the direction of the arrow and is in the position *ac* when a drop is just entering, then, if it moves at such a velocity that it reaches the position *bd* by the time the drop has fallen through the distance *cb*, the drop will have passed along the tube without touching the sides.

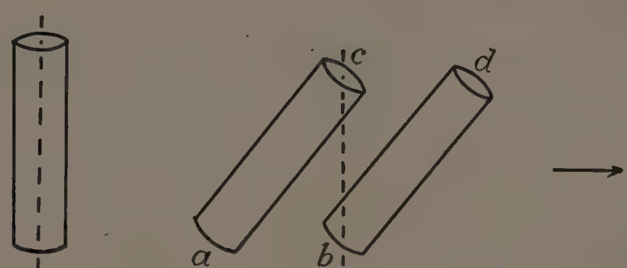


Fig. 12.

The angle *cbd* through which the tube is tilted will depend upon the velocities of drop and tube, and is called the *angle of aberration.* The tube must always be tilted in the direction of its own motion.

If a star at the pole of the ecliptic were observed from a stationary earth, the telescope would be pointed directly at the star, but since the earth's orbital velocity is 30 km per second the telescope must be tilted forward in the direction of the earth's motion by a small angle in order to allow the rays of light from the star to pass through the instrument. When the earth is at *A* (Fig. 13) the telescope must be tilted to the right, when at *B* to the left, when at *C* toward the reader and when at *D* away from him.[1]

A star at the pole of the ecliptic will therefore appear to move around in a small orbit of exactly the shape of the earth's orbit. The angle of aberration is about $20''.5$, hence the major axis of the aberrational orbit will be $41''$. For a star in the plane of the ecliptic there will be no aberration when the earth is moving

[1] It must be remembered that the stars are so far away that their rays are practically parallel, and for a star at one of the poles of the ecliptic these rays are perpendicular to the plane of the earth's orbit.

directly toward or away from it, but the maximum effect will be found when the earth is moving perpendicularly to the star's direction. The star will therefore appear to move back and

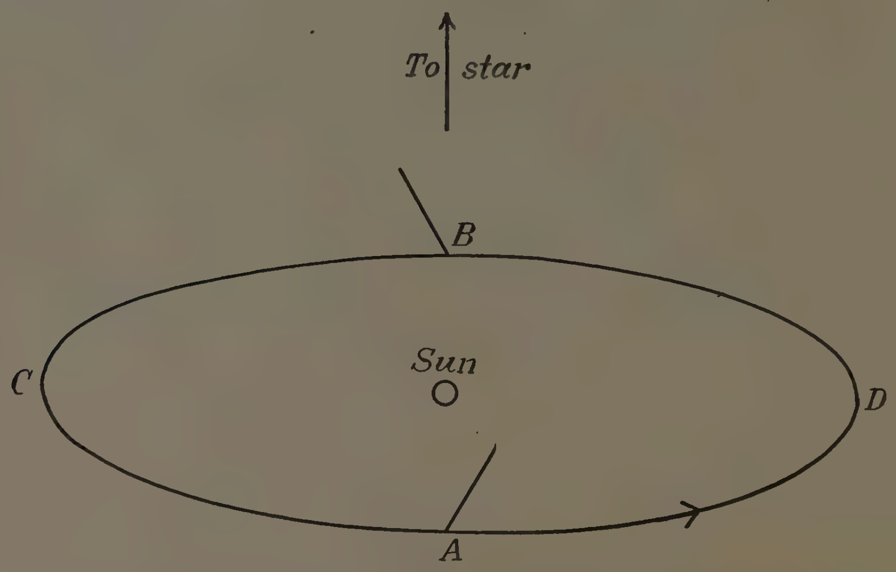


FIG. 13.—The aberration of light. The tilting of the line of sight is greatly exaggerated in the figure.

forth along a straight line 41″ in length. For a star between the plane of the ecliptic and its pole the aberrational orbit will be an ellipse of greater or less eccentricity, depending on its distance from the pole of the ecliptic.

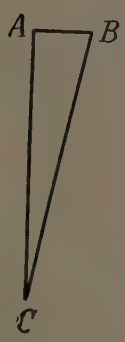


FIG. 14.

The aberration of light was discovered by Bradley in 1726. It is a definite proof that the earth revolves about the sun.

25. The Sun's Distance by Aberration.—In Fig. 14 let CA represent the velocity of light and AB the velocity of the earth in its orbit. If we can measure accurately the angle of aberration C, we can compute the velocity of the earth. Knowing the earth's velocity, we can find the circumference of its orbit and hence its radius.

The velocity of light has been measured with considerable accuracy. By trigonometry we write

$$AB = 299{,}820 \text{ km} \times \tan 20''.5$$

and thus determine AB, the earth's velocity.

26. The Seasons.—If the axis of the earth were perpendicular to the plane of the ecliptic, the sun would always be on the celestial equator and hence the days and nights always equal in length. Under such conditions there could be no change of seasons as is now the case.

Since the axis of the earth is tipped about 23°.5 from the perpendicular to the plane of its orbit, it is evident that when the earth is at *C* (Fig. 15) in its orbit the sun shines perpendicularly on a point 23°.5 north of the equator, shines past the north pole 23°.5 and fails by a like amount of shining on the south pole. Three months later, when the earth is at *D*, the sunlight just reaches both poles and falls perpendicularly at the

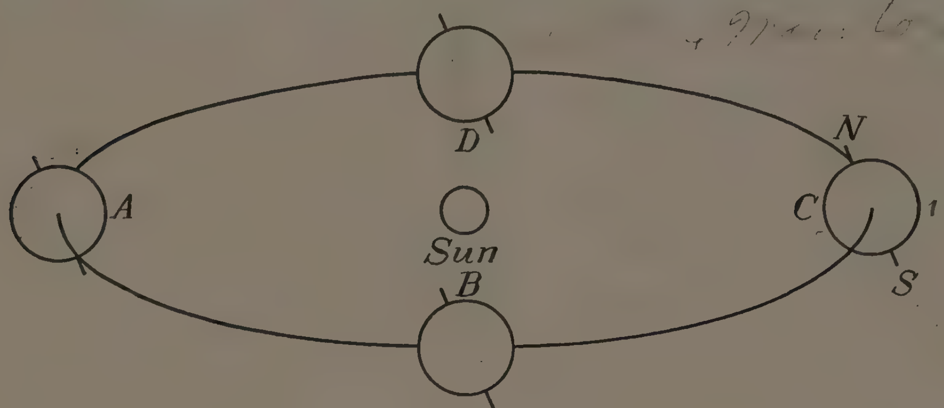


Fig. 15.—Cause of the seasons.

equator. Three months later still, when the earth is at *A*, conditions are just opposite to what they were at *C*, while after another interval of three months, when the earth is at *B*, the sunlight again just reaches both poles. During the time the earth is near *C* the northern hemisphere has its summer and the southern its winter, while, when the earth is near *A*, the opposite condition prevails. When the earth is at *B* we have the spring or vernal equinox and when at *D* the autumnal equinox.

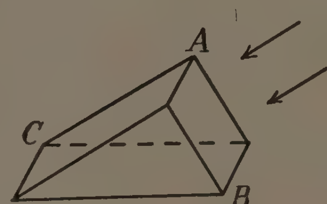


Fig. 16.

The season at any point on the earth depends upon the amount of sunlight that region receives, the more sunlight the warmer the season. The daily amount of sunshine per unit of area depends upon two factors, the elevation of the sun above the horizon and the duration of the daylight. It is evident, from Fig. 16, that if the incoming rays fall on a surface *AB* which is perpendicular to them, each unit of area of *AB* will receive more heat than a unit of area of a surface *CB* which is not perpendicular to them. Even a low sun, however, if it shines through a long day, may furnish more heat in the course of such a day than a high sun shining for a shorter time. Thus, neglecting atmospheric absorption, during the long days of summer the north pole actually receives more heat from the sun in the course of 24 hours than does a region near the equator.

CHAPTER III

THE CELESTIAL SPHERE

27. Celestial Sphere.—When we look at the sky at night the stars seem to be fixed on the inside of a spherical surface and we appear to be at the center. This spherical surface is called the *celestial sphere,* but the term includes not only the hemisphere above the horizon but also the hemisphere below. The stars are so far away that we can assume the radius of the sphere to be practically infinite. This implies that any two parallel lines a measurable distance apart, if extended until they reach the celestial sphere, will appear to intersect it at the same point, the "vanishing point" of the two lines.

The celestial sphere is only apparent, however, for some of the stars are relatively near and others are far away.

28. Position and Distance on the Celestial Sphere.—When two stars are said to have practically the same position in the sky we mean that they have practically the same direction as seen by the observer. Thus in Fig. 17 stars *a* and *b* would be said to be in about the same position in the sky even though *b* might be 2 or 200 times as far from the observer as *a*. Two stars are said to be close together when lines drawn to them make only a small angle with each other, and they are said to be far apart when these lines make large angles. The observer at *O* would thus say that star *a* is closer to star *b* than to star *c*, even though in reality *a* might be many times farther away in space from *b* than from *c*. The reason for this is that the real distances to most of the stars are not known with any degree of accuracy, and we are therefore compelled to resort to direction alone. Hence, distances in the sky must be given in angular measure, in degrees, minutes and seconds.

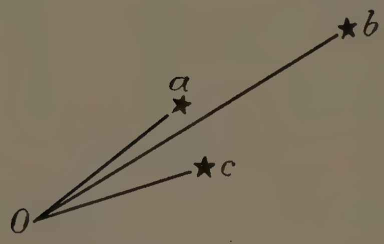


Fig. 17.

Persons who have had no experience in observing sometimes say that two stars look to be a foot apart. This, of course, is misleading unless they also state how far from the eye the foot

rule is to be held. If this information is added, the angular distance can be determined.

Until the student has become accustomed to estimating angles the following values will be helpful. A rough measure for an angle of 1° is the apparent diameter of a dime held at arm's length from the eye. The apparent diameter of sun or moon is about half a degree, while the longest side of the bowl of the Big Dipper is about 10°.

29. Zenith, Nadir, Horizon.—The plumb-line indicates the direction of gravity at any point. The point of the celestial sphere where the plumb-line extended cuts the sphere overhead is called the *zenith* and the opposite point the *nadir*. The circle of the sphere half way between zenith and nadir is called the *horizon*. It might also be defined as the intersection of the celestial sphere by a plane tangent to a level surface at any point on the earth where the observer is located. The plumb-line is always perpendicular to a level surface, and is therefore perpendicular to the plane of the horizon.

The visible horizon, obstructed as it may be by trees, buildings or elevations of land, must not be confused with the astronomical horizon as defined above.

30. The Horizon System of Circles.—It is frequently desirable to indicate how high a star may be above the horizon and also in what direction it may be found. For this purpose a system of circles is used which is analogous to the system of meridians and parallels on the earth. For the latter we take two points directly opposite each other on the earth, which we call the poles. Then the fundamental circle, the equator, is passed around the earth half way between the poles. Finally, two groups of secondary circles are added, the parallels of latitude which are parallel to the fundamental circle and the meridians which pass through the poles and are perpendicular to the fundamental circle.

The horizon system in a similar way uses the horizon as its fundamental circle with its poles at zenith and nadir. Through the zenith and nadir are passed the *vertical circles*, which will be perpendicular to the horizon. A second set of circles, the *parallels of altitude*, are arranged so as to be parallel to the horizon. almucantar

In Fig. 18, Z amd X are zenith and nadir respectively. The horizon circle, $NWSE$, lies half way between them, N being

the north point, W the west point, etc. Circles like $ZBXT$ are the vertical circles and those like $CDFG$ are the parallels of altitude. The observer is at O.

31. Altitude and Azimuth.—If an observer at O sees a star in the direction OA, then the line OA makes an angle BOA with the horizon plane. This angle (in degrees) measures the height of the star above the horizon and is equal to the arc AB, of the vertical circle through A. This angle is called the *altitude* of the star above the horizon.

Altitude alone however will not define the star's position for all points on the parallel of altitude $AFGC$ have the same altitude. The vertical circle ZSX, accordingly, is used as a starting point and the angle SZB at the zenith, or its equivalent in degrees, the arc SB, measures the direction from the circle ZSX. This angle SZB is called the *azimuth* of the star A.

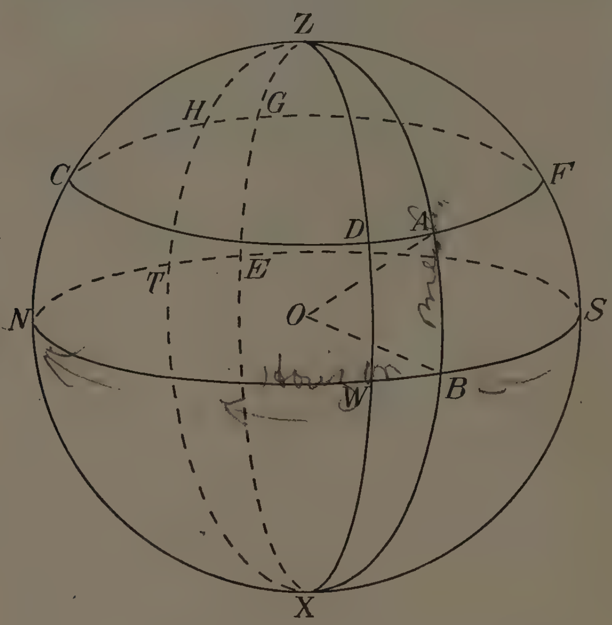


FIG. 18.—The horizon system of circles.

Azimuth is reckoned all the way around the horizon up to 360° beginning from the south point and going through the west. Thus, a star H, seen in the ENE, would have an altitude HT and an azimuth SZH equal to 247°.5.

The two quantities, altitude and azimuth, are called the *coordinates* of a celestial body in the horizon system. The vertical circle NZS is called the *celestial meridian* and the vertical circle EZW, which cuts NZS at right angles, is called the *prime vertical.*

32. Disadvantages of Horizon System.—The horizon system is of value in locating an object in the sky with reference to the horizon, but it is useful only for a single location, for it is evident that, since each observer has a different zenith from every other observer, no two observers have the same horizon. The altitude and the azimuth of a heavenly body, while being nearly the same if two observers are near each other, will differ greatly if

the observers are far apart. Furthermore, since the earth rotates the altitudes and the azimuths of the heavenly bodies are constantly changing. It is, therefore, desirable to have a system of circles whose positions are referred to the stars themselves. Such a system is the equator system.

33. The Equator System.—In Sec. 18 we learned that there are two points directly opposite each other in the sky, the celestial poles, around which the stars appear to revolve. These two points are determined by the direction of the earth's axis, and, except for a very slow motion to be considered later, may be considered fixed among the stars.

The earth's equator lies midway between the terrestrial poles and its plane is perpendicular

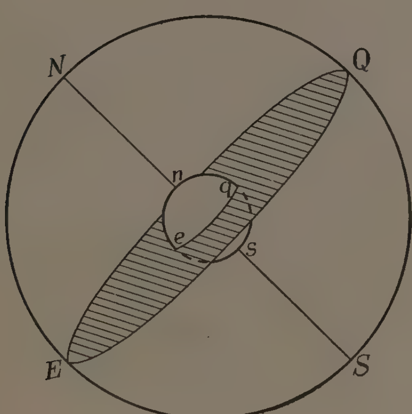


FIG. 19.

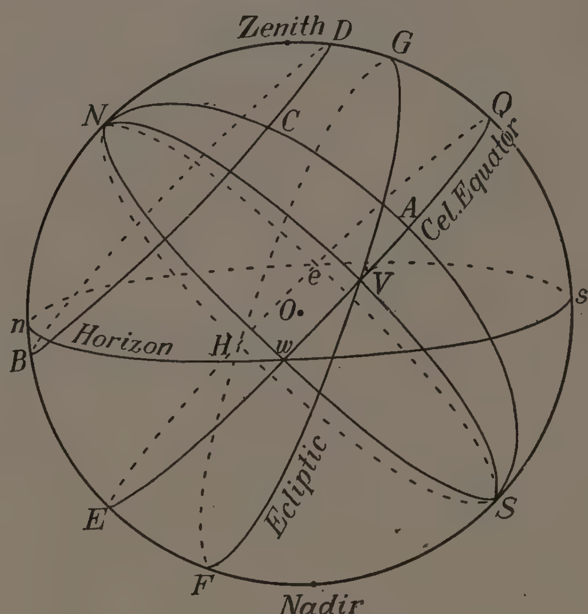


FIG. 20.—The equator system of circles.

to the earth's rotation axis. Accordingly, if we extend the plane of the earth's equator outward indefinitely until it appears to intersect the celestial sphere, this intersection will be a circle, called the *celestial equator*, which will be just half way between the celestial poles. Figure 19 illustrates this.

We are thus presented with a fundamental circle EQ and its poles N and S, and can draw secondary circles just as in the horizon system.

34. Hour Circles and Parallels of Declination.—The secondary circles drawn through the celestial poles and perpendicular to the celestial equator are called *hour circles*, while the secondary circles drawn parallel to the celestial equator are called *parallels of declination* (Fig. 20).

The north and south points of the horizon are actually determined by the vertical circle passing through the celestial poles. The hour circle passing through the zenith will, therefore, pass through the north and south points and coincide with the meridian.

35. The Equinoxes and Solstices.—In Sec. 23 the ecliptic was defined as the apparent path of the sun as it moves eastward among the stars. The plane of the ecliptic makes an angle of approximately 23°.5 with the celestial equator. In Fig. 20 the circle *FG* represents the ecliptic and the circle *EQ* the celestial equator. These intersect at two points *V* and *H*. The point *V*, where the sun crosses the celestial equator from south to north, is called the *vernal equinox.*[1] When the sun is at this point, spring commences in the northern hemisphere. The other point *H*, where the sun crosses the celestial equator from north to south, is called the *autumnal equinox,* and the instant of crossing marks the beginning of the northern autumn.

The two points on the ecliptic half way between the equinoxes are called the *solstices.* The one north of the celestial equator is called the *summer solstice* and the one south of the equator the *winter solstice,* since the sun is at these two points at the beginning of summer and winter respectively in the northern hemisphere.

36. Right Ascension and Declination.—The hour circle *NVS*, passing through the vernal equinox, is used as the zero hour circle and angles are measured from this circle eastward through 360°. This coordinate is known as *right ascension.* Thus a star at *C* will have a right ascension of about 15°.

Angular distance north or south of the celestial equator is known as *declination.* The star at *C* has a declination of about +40°, the plus sign indicating north declination. South declination is indicated by the minus sign.

A star at *F* would have a right ascension of about 250° and a declination of −23°.5.

Right ascension is usually measured by means of a clock and it is therefore more convenient, in general, to express this coordinate in time rather than in degrees of arc. For this purpose 1 hour of time is equivalent to 15° of arc. Hence the position of a star at *C* would be given as R. A. 1^h, Dec. +40°, while the position of a star at *F* would be R. A. $16^h\ 40^m$, Dec. −23°.5.

37. Hour-angle.—It is often convenient to use an angle known as *hour-angle.* It is the angle which any given hour circle makes

[1] This point is also called the *First of Aries.*

with the celestial meridian and is measured toward the west. If the sun is on the celestial equator and just rising, its hour-angle is 18^h. Four hours later its hour-angle is 22^h, and when it is on the meridian the hour-angle is 0^h.

Sometimes it is convenient to say that an object is a certain number of hours east or west of the meridian, meaning either that it will be on the meridian in that number of hours or that it was on the meridian that many hours ago. This form of expression must not be confused with the term hour-angle as defined above.

38. Celestial Longitude and Latitude.—For some purposes another system of coordinates is used. This is called the *ecliptic system* because the ecliptic is taken as the fundamental circle and the poles of the ecliptic, two opposite points 90° from the ecliptic, are used as poles. The poles of the ecliptic are about 23°.5 from the corresponding celestial poles.

The secondary circles passing through the poles of the ecliptic and perpendicular to the ecliptic are called *circles of latitude*, while those drawn parallel to the ecliptic are called *parallels of latitude*.

The coordinates in this system are known as *celestial longitude* and *latitude*. The longitude is measured eastward from the vernal equinox all the way around the sphere, while the latitude is the angular distance north or south of the ecliptic.

The ecliptic system is used when we wish to refer the motions or positions of planets to the sun which is always in the ecliptic. It is not possible to observe celestial longitude and latitude directly. If they are employed, the right ascension and the declination are determined by observation and then converted into celestial longitude and latitude by calculation.

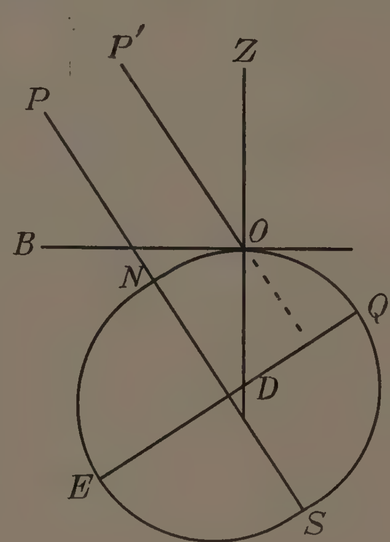


FIG. 21.

39. Summary.—Table I on page 30 shows the similarity between the various systems considered.

40. Relation between Latitude and Altitude of Pole.—In Fig. 21 let NS be the earth's axis, EQ the plane of the equator, O the observer, ZOD the direction of the plumb-line, BO the plane

TABLE I

	The earth	The celestial sphere		
		Horizon system	Equator system	Ecliptic system
Fundamental circle...........	Equator	Horizon	Celestial equator	Ecliptic
Poles.......................	North and south terrestrial poles	Zenith and nadir	North and south celestial poles	North and south poles of ecliptic
Secondary circles..............	Meridians and parallels	Vertical circles and parallels of altitude	Hour circles and parallels of declination	Latitude circles and parallels of latitude
Coordinates..................	Longitude and latitude	Azimuth and altitude	Right ascension and declination	Celestial longitude and latitude
Zero circle..................	Meridian through Greenwich	Vertical circle through south point	Hour circle through vernal equinox	Latitude circle through vernal equinox
Direction of first coordinate....	East and west	Through west	Eastward	Eastward

of the horizon, NP the direction of the celestial pole and OP' a line parallel to NP.

Since the line OP' is parallel to NP, the prolongation of the earth's axis, the two lines will meet when extended to the celestial sphere. Accordingly, the angle BOP' will be the angle of elevation of the celestial pole above the observer's horizon. The angle ODQ, the angle between the observer's plumb-line and the plane of the equator, will be his astronomical latitude. The point D, in general, is not at the earth's center (see Sec. 12).

BO is perpendicular to OD and $P'O$ is perpendicular to DQ. Hence angle $P'OB$ is equal to angle ODQ, or *the altitude of the celestial pole is equal to the astronomical latitude of the observer.*

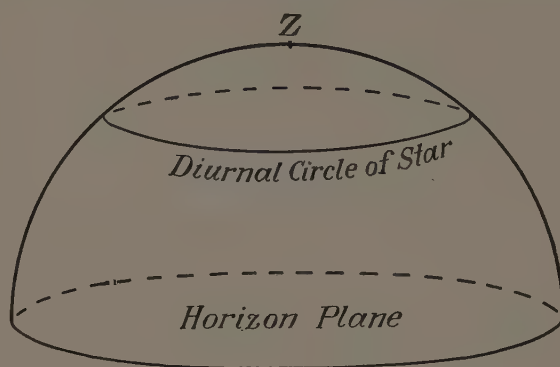


FIG. 22.—The parallel sphere.

41. The Parallel Sphere.—If an observer were located at one of the poles of the earth the celestial pole would be located in the zenith. The stars would then all revolve around the zenith in circles which would be parallel to the horizon, and hence the name of parallel sphere. For such an observer no stars would ever rise or set (Fig. 22).

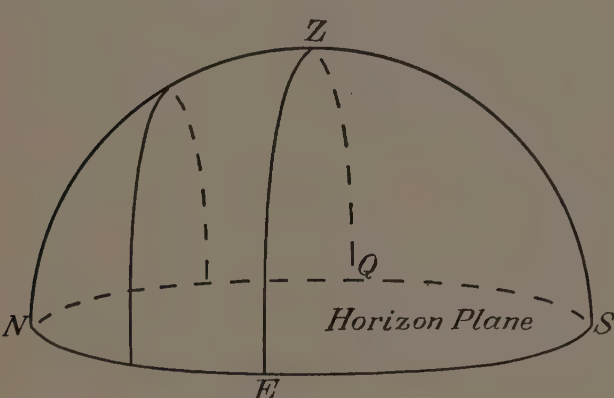


FIG. 23.—The right sphere.

42. The Right Sphere. For an observer at the equator the celestial poles would lie in the north and south points of the horizon and the celestial equator would pass through the zenith. For such an observer all stars would rise and set, their visible paths being semi-circles parallel to the celestial equator as shown in Fig. 23.

43. The Oblique Sphere.—For an observer anywhere between equator and either pole, the celestial pole would be at an altitude equal to his latitude. In consequence, stars near the elevated pole would move around the latter in circles, the stars near the pole below the horizon would never be seen, while the remaining

stars would be at times above and at other times below the horizon and would move in circles oblique to the horizon (Fig. 20).

44. Angular Measurement—The Radian.—The circumference of a circle is usually divided into 360 equal parts called *degrees.* The degree is divided into 60 equal parts called *minutes of arc* and the minute of arc into 60 equal parts called *seconds of arc.* These various arcs subtend corresponding angles at the center of the circle which are called degrees, minutes and seconds of angle. Where no ambiguity exists the phrases "of arc" and "of angle" are usually omitted.

If an arc of a circle is laid off equal to the radius, it subtends an angle at the center known as a *radian.* The value of the radian is evidently $\frac{360°}{2\pi}$. In the various units a radian is equal to $57°.3$, $3437'.7$ and $206{,}264''.8$ when values to the nearest tenth of each unit are used.

45. Relation between Angular Diameter and Distance.—If an object subtends an angle of 1° its diameter is practically equal in length to 1° of arc of the circle whose center is at the eye of the observer. Thus, in Fig. 24, if the object whose diameter is the chord CB subtends an angle equal to 1° at the point A, the diameter CB will be very nearly equal to the arc CB whose center is at A. Since the arc CB is $\frac{1}{57.3}$ of radius AB, the diameter CB will be very nearly equal to the same fractional part of AB.

Fig. 24.—Relation between angular diameter and distance.

The smaller the angle subtended at A the nearer will the chord CB equal the arc CB in length. We may, therefore, say that if a body subtends an angle of 1° its diameter is approximately equal to $1/57$ of its distance; if the body subtends an angle of $1'$ its diameter is equal to $1/3438$ of its distance, while if it subtends an angle of $1''$ its diameter is equal to $\frac{1}{206{,}265}$ of its distance.

This relation between angular diameter and distance is of great importance, for if either diameter or distance is known in linear units, such as miles or kilometers, the other may be immediately determined.

CHAPTER IV

LIGHT

Practically all of the information of the heavenly bodies is obtained by means of the light they send us through space. It is therefore desirable that some of the elementary considerations concerning light be taken up.

46. The Ether of Space.—It is believed that all space is filled with a certain substance which is called the ether. This ether penetrates all bodies. Under certain conditions the ether may be in a state of strain and it is considered to be highly elastic. Much has been written about the ether, but, as a matter of fact, its actual existence has never been proved conclusively. It has seemed necessary, however, to assume its existence in order to account for many phenomena, such as light, magnetic and electrical fields, etc.

In general, it has been found impossible to describe in a mechanical way the transmission of light, gravitation, etc., across absolutely empty space. Some means of transmission or medium seems necessary. This medium is called the *ether*. The necessity for such an assumption is partly philosophic and partly scientific. Some scientists hold that an ether is not essential to the explanation of physical phenomena, but the scientific world in general holds to the ether theory. In this book we shall follow the majority and assume the existence of the ether.

47. The Nature of Light.—Light is generally described as a wave-motion in the ether. The vibration is at right angles to the direction of the ray of light, just as in a water wave the vibration of the water particles is up and down, while the wave-motion itself travels horizontally. Many experiments have been devised to prove the wave-theory of light, and in every case the results have been either in accord with the wave-theory or have not opposed it. No experiment has yet been devised which succeeded in disproving the theory.

48. Wave-length, Vibration Frequency and Velocity of Light. In a water wave the distance between two successive crests or

troughs, such as *bf* or *dh* (Fig. 25), is called the *length* of the wave. The distance which a wave will travel in a unit of time, such as 1 second, is the *velocity* of the wave. When a train of waves passes a given point a water particle at that point will make one upward and one downward motion for each wave of the train. The upward and downward motion together is called one complete vibration, and it is evident that a particle of water will make as many vibrations in 1 second as there are waves passing per second. The number of vibrations per second is called the *vibration frequency*. The relation between wave-length, frequency and velocity is given by the equation

$$v = n\lambda,$$

where v is the velocity of the wave train, n the vibration frequency and λ the wave-length.

In an analogous manner we may speak of the velocity, vibration frequency and wave-length of light in the ether or other transparent medium.

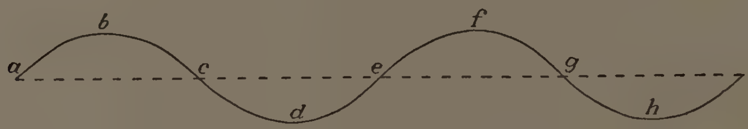


FIG. 25.

The velocity of light can be determined in a number of ways, and all modern methods give substantially the same results. The most recent, and probably most reliable, value is that obtained by Michelson in 1924—299,820 km (186,339 miles) per second in a vacuum. This value is believed to be within 30 km (20 miles) of the true value.

Just as water waves differ in length, so ether waves differ. The unit of length for the ether wave used in radio communication is the meter, and the length of these waves varies from a few meters to many thousands. When we consider the wave-length of light a much smaller unit is desirable and the one now in general use is the one ten-billionth ($1/10^{10}$) of 1 meter and is called the Angstrom, which is abbreviated to A. Deep-red light has a wave-length of about 7800 A, yellow light about 5900 A and violet light about 3900 A. The Greek letter lambda, λ, is usually used as a symbol for wave-length.

Owing to the extremely high velocity of light and the exceedingly short wave-length, the vibration frequency is expressible

only by very large numbers. Thus the frequency for deep-red light is of the order of 400,000000,000000 or 4×10^{14}, while the frequency for violet light is of the order of 8×10^{14}.

49. The Atomic Theory.—The unit of matter usually dealt with by the chemist is called the *atom*. There are at present 90 different kinds of atoms known which distinguish the various chemical elements. Thus we have atoms of hydrogen, helium, sodium, iron, silver, gold, etc. It has been possible to determine the relative weights of the various atoms beginning with the lightest, hydrogen, which is arbitrarily said to have an atomic weight of 1. On this basis helium has an atomic weight of 4, sodium 23, iron 56, etc. The heaviest atom known is that of uranium, with an atomic weight of 238.

In recent years it has been found that the atom is not the ultimate unit, but that the structure of the atom, in general, is rather complicated. Evidence is now accumulating that all the atoms of the various chemical elements are in reality composed of but two things, called protons and electrons. The hydrogen atom appears to consist of one proton and one electron, the simplest possible combination. The proton is the nucleus of this atom, weighs about 1800 times as much as the electron and carries a positive charge of electricity. The electron is the unit of negative electricity. On this theory the nuclei of other elements are composed of a number of protons and electrons with certain electrons outside the nucleus to complete the atom. Thus the uranium atom has 238 protons and an equal number of electrons, all the protons and about 146 electrons being in the nucleus and the other electrons being arranged outside.

50. The Bohr Theory of the Atom.—The source of the ether vibrations which we call light lies in the atom. The exact connection is still unknown, but it will aid in our attempt to understand the phenomenon by stating in outline the extraordinarily interesting theory of atomic structure developed by Bohr of Copenhagen. We shall consider only the atom of hydrogen as it is the simplest case.

Bohr assumes that the nucleus of this atom, which has one positive charge of electricity, is a center around which a single electron, which is a negative charge, revolves. The force holding the two together is the electrical attraction of the two charges. The electron may move in any one of a number of orbits or paths (Fig. 26), which are spaced about the nucleus with radii

in the ratio of 1, 4, 9, 16, etc., although the inner one is the normal one. So long as the electron is moving in any one of these paths or orbits nothing seems to occur, but, if energy is added from without, the electron is forced away from the center and compelled to move in one of the outer orbits. The greater the amount of energy added the farther the electron is separated from the nucleus, and it may be driven away altogether.

If the electron, while in one of the outer orbits, drops to one of the inner ones it gets rid of some of its energy and it is this energy which is radiated into space as an ether vibration, the period of the vibration depending both on the number of the orbit from which it falls and the number of the one to which it falls. Thus, if the electron falls from orbit 3 to orbit 2 the vibration has a wave-length of 6563 A; if from orbit 4 to orbit 2 the vibration has wave-length 4861 A, etc., the greater the fall the more rapid

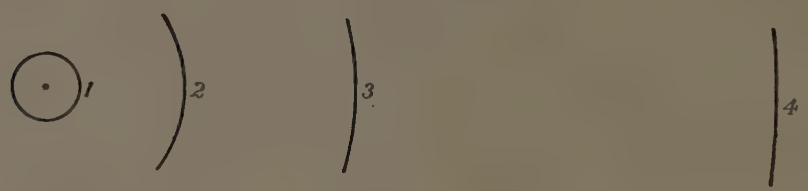


FIG. 26.—The spacing of orbits of the electron of the hydrogen atom, according to the Bohr theory.

the vibration. In the light of some stars hydrogen gives evidence of having vibrations of 27 different frequencies (Fig. 144). When an atom is radiating energy the electron is approaching the nucleus, while when the atom is absorbing energy the electron is being forced away from the nucleus.

For atoms heavier than hydrogen, with a number of electrons revolving about the nucleus, the theory becomes very complicated, but Bohr and others have succeeded so brilliantly in explaining many relationships of light waves, and in predicting others which later have been found experimentally, that this theory of atomic structure is now quite generally accepted as one of the great advances toward an exact knowledge of the real structure of the atom.

If an atom has lost one or more of its outer electrons it is said to be *ionized*. When in this condition it can capture stray electrons which come within its sphere of influence. As these are drawn in and pass from outer to inner orbits they radiate light as stated above. Accordingly, an atom, when ionized, is

in a condition to radiate energy as soon as an electron can be captured.

51. Refraction and Dispersion of Light.—When a ray of light, consisting of vibrations of the same wave-length (monochromatic light), passes from a rarer medium such as air to a denser medium such as glass the ray is bent toward the perpendicular to the surface separating them, as at A (Fig. 27). When the ray passes from a denser to a rarer medium it is bent away from a similar perpendicular, as at B. This bending of the ray is called *refraction.*

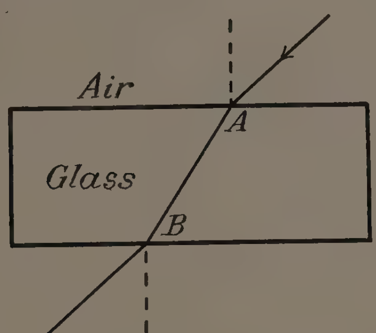


FIG. 27.—Refraction of light.

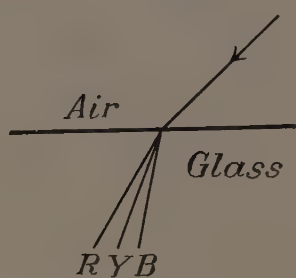


FIG. 28.—Dispersion of light.

Light of different wave-lengths is refracted differently under the above conditions, the shorter the wave-length the greater the refraction. Thus, since red light has a longer wave-length than yellow light it is refracted less, and yellow light, in turn, is refracted less than blue light. If a ray of light should, therefore, be composed of light of each of these colors the effect of passing from air to glass is illustrated in Fig. 28. This decomposition of a ray of light into its constituent colors is called *dispersion.*

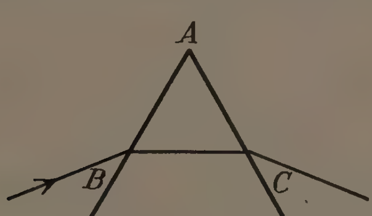


FIG. 29.—Refraction of light by a prism.

FIG. 30.—Dispersion of light by a prism.

52. Path of Ray through a Prism.—If a narrow beam of monochromatic light is allowed to pass through a prism of glass, the path followed is shown in Fig. 29, the amount of deviation depending on the refracting angle, A, of the prism, the density of the glass composing the prism and the angle at which the beam strikes the prism face. For most purposes it is convenient to

have the two angles B and C equal. In this case the beam goes through the prism parallel to the base and the total deflection is a minimum.

If, instead of using monochromatic light, the beam consists of light of various wave-lengths, then dispersion also takes place and the beam is separated into its constituents, as shown in Fig. 30, which illustrates the effects for red, yellow and blue light. A prism used in this way analyzes a beam of light into its constituent parts. This property of the prism is used in the spectroscope described later (Sec. 72).

53. The Achromatic Prism.—If two prisms of the same kind of glass are used as shown in Fig. 31 the dispersion of the one is practically neutralized by the other and the ray emerges from the combination in a path parallel to the original path but displaced with respect to the latter.

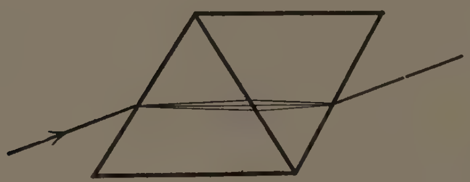


FIG. 31.

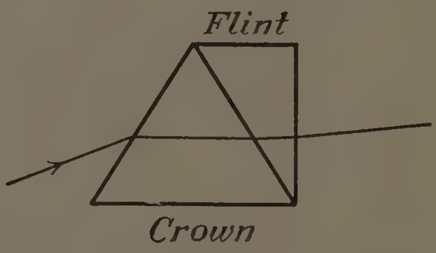


FIG. 32.—The achromatic prism. Dispersion of light within the prisms not indicated.

Similar prisms made of two common kinds of glass, crown and flint, give about the same refraction for rays of light traversing them, but the flint-glass prism gives about double the dispersion of the crown-glass prism. This property of the two kinds of prisms is used if we wish to refract a beam of light without separating it into its various constituents. A crown-glass prism is combined with a flint-glass prism of about half the angle, as shown in Fig. 32. The second prism neutralizes the dispersion of the first but only half the refraction. Hence the beam of light is refracted by the combination without being dispersed. Such a compound prism is called an *achromatic prism.*

54. The Nature of White Light.—If a beam of white light is analyzed by means of a prism, it is found to be made up of ether waves of all lengths from about 7800 to 3900 A. These waves of different lengths affect the eye as different colors which merge into each other in the order red, orange, yellow, green, blue and violet as we go from the longer to the shorter waves.

By appropriate methods it has been found that white light also contains waves both longer than 7800 and shorter than 3900 A. These are called infra-red and ultra-violet waves respectively.

55. Shapes of Lenses.—A lens is usually a piece of glass bounded either by two spherical surfaces or by one spherical and one plane surface. Figure 33 shows sections of the six ordinary kinds of lenses. They are called, in order, double convex,

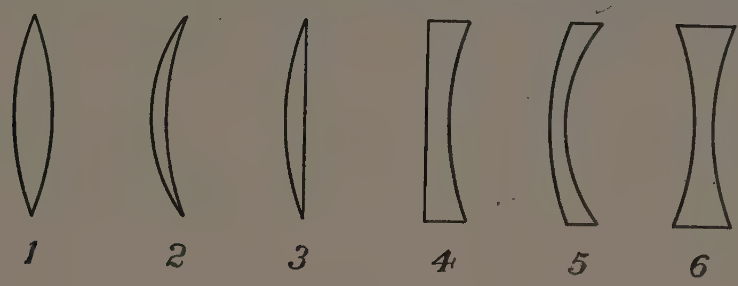


FIG. 33.—Types of lenses.

concavo-convex or meniscus, plano-convex, plano-concave, concavo-convex and double concave. Numbers 2 and 5 cannot be distinguished by their names alone.

A lens is used either to converge or to diverge a beam of light. The first three are convergent lenses and the last three divergent. The converging lenses are thicker at the center than at the edge, while the divergent lenses are thinner.

56. Convergent Lenses.—The ordinary use of a convergent lens is to form an image of an object. A simple Kodak or camera

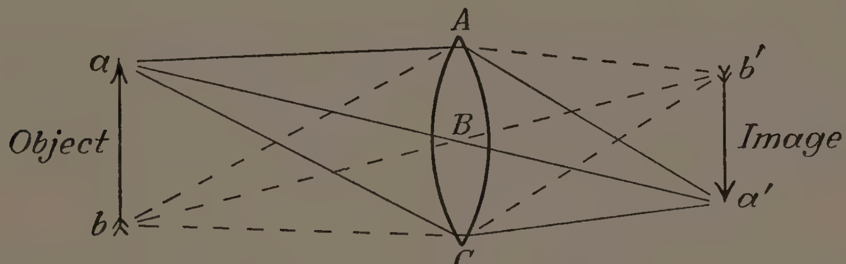


FIG. 34.—Formation of an image by a convergent lens.

is the best-known illustration. The use of double-convex lens for this purpose is illustrated in Fig. 34, but the principle is the same for all convergent lenses. By means of the figure we shall trace three rays from each end of the arrow and assume that we are dealing with monochromatic light. The ray from point a which strikes the upper portion of the lens at A is bent as if the lens were a prism, and sent to a'. The ray passing through the center B is essentially undeviated, while the ray passing through C is

deviated in the opposite direction from that through A so that the three unite at a'. Other rays from a which strike the lens between A and C are deviated proportionally, so that they all unite at a'.

In a similar manner the rays from b are united at b' and rays from other parts of the arrow shaft between a and b unite at corresponding points between a' and b', so that an image of the arrow is formed. This image may be seen very easily if it is allowed to fall on a piece of white paper or on a ground glass, as in the larger photographic cameras.

57. Focal Length of Convergent Lens.—If a beam of light from a very distant source, such as a star, passes through a lens (the light from the source consisting of parallel rays) an image of the star is formed at a definite distance from the center of the lens. This distance is called the *focal length* of the lens and depends upon the density of the glass and the curvature of the lens surfaces. The greater the density of the glass and the greater the curvature of the surfaces the shorter the focal length of the lens.

If it is desired to use a parallel beam of light a point source may be placed at the focus of a lens as shown in Fig. 35. Such an arrangement is of importance in some optical instruments, such as the spectroscope.

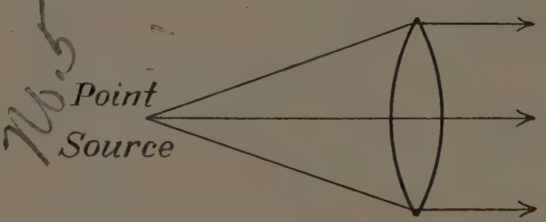


FIG. 35.—Production of a parallel beam of light.

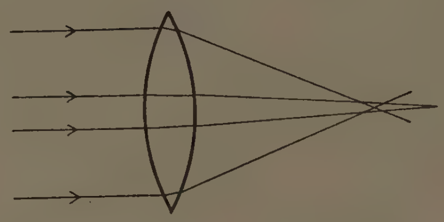


FIG. 36.—Spherical aberration.

58. Spherical Aberration.—Thus far we have considered only the general action of a convergent lens. In order to understand the telescope it is necessary to consider the matter more minutely. If rays of light from a distant point source pass through a convergent lens it is found that the image is not formed at a point because the rays going through the lens near the edge are brought to a focus nearer the lens than those passing through near the center. This is illustrated in Fig. 36. This action of the lens is called *spherical aberration*. The thicker the lens in proportion to its diameter the greater the spherical aberration.

59. Chromatic Aberration.—Because of the dispersion of light by glass a very troublesome color effect is also in evidence. The focal length of a lens for blue light is less than for yellow and for yellow light less than for red. In consequence, if an object is sending out light of these three colors, the image formed will not be a single image but there will be blue, yellow and red images formed at increasing distances from the lens. This effect is called *chromatic aberration,* and is illustrated in Fig. 37, the images and object alone being shown without tracing the rays.

If light of many wave-lengths (white light) comes from the object there will be an image for each wave-length—the longer the wave the farther the image will be from the lens.

FIG. 37.—Chromatic aberration.

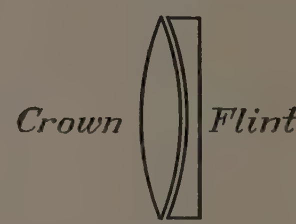


FIG. 38.—An achromatic lens.

60. The Achromatic Lens.—In order to avoid the very troublesome chromatic aberration of lenses, it has been found possible to utilize the principle considered in the achromatic prism (Sec. 53). By combining a double-convex lens of crown glass with a plano-concave lens of flint glass, as shown in Fig. 38, an image is obtained which is reasonably free from color. Such a lens is called an *achromatic lens.* Lenses of this kind appear to have been made first by Chester Moor Hall of England in 1733, but they were first made for general use by the English optician, Dollond, in 1758.

Strictly speaking, a double lens of this character will combine accurately light of only two colors or wave-lengths. For some purposes it is desirable to combine three or more colors in the image. When this is the case three or more lenses of different optical properties must be used.

In addition to eliminating the chromatic aberration by such lens combinations it is also possible to eliminate most of the spherical aberration by a proper choice of curvature of the lens surfaces. For large lenses the flint component is not plane on one side, as shown in Fig. 38, but has this side ground to a slight curve as well.

CHAPTER V

ASTRONOMICAL INSTRUMENTS

THE REFRACTING TELESCOPE

61. Invention of the Telescope.—It appears uncertain who should be called the inventor of the telescope. Certain references lead some to think that the instrument was not unknown to the Greeks and Romans, but, if this was the case, it never came into general use. From the practical point of view it appears that telescopes were first made in Holland about 1608. The following year Galileo heard of the invention and constructed a number of instruments which magnified from 3 to 33 times. In 1610 he began his series of astronomical observations and discoveries and thus was the first to demonstrate the enormous value of this most important instrument to astronomy.

62. Principle of the Telescope.—The principle of the telescope is exceedingly simple. All that is required is a lens (called the object glass or objective) to form an image of the object to be

FIG. 39.—The principle of the refracting telescope.

examined, a magnifier (called the eye-piece) to magnify the image and some device, such as a tube, to hold them the requisite distance apart.

The principle is most easily illustrated by means of a camera. If the camera is pointed at a tree, as indicated in Fig. 39, an image of the tree will be formed on the ground glass at the back. For focusing purposes this image is usually examined directly by the eye, but if we magnify the image by means of a simple pocket lens we shall have a telescope in a crude form.

The ground glass has nothing to do with the formation of the image but is a convenient device for determining the focus of the

camera. If the image is examined without the ground glass it will be found brighter than with it.

Let us now apply this principle to the telescope. Suppose the instrument is pointed at the moon (Fig. 40). An image of the moon will be formed by the objective near the eye end of the tube. This image is then magnified by the eye-piece so that the eye will see the moon apparently much enlarged as compared with the naked-eye view.

Fig. 40.—A refracting telescope.

63. The Objective.—The purpose of the objective is twofold: (1) to gather as much light as possible from the object; and (2) to form an image of the object, which may then be magnified by the eye-piece. The larger the objective the more light it can collect from the object. This is of no especial importance for a bright object like the moon, but for a faint object like a distant star it is of the utmost importance, for the image must be bright enough to affect the retina of the eye. For work on faint objects telescopes of large aperture are therefore necessary.

Other things being equal, the large objective also has another advantage over the small one. The image of a star consists of a bright central disc surrounded by a series of concentric bright rings. The disc is called the *spurious disc*. The large objective forms a relatively smaller spurious disc than the small one, so that if two stars are so close together that their spurious discs overlap and they cannot be seen separately in the small telescope they may not overlap in the large one and thus appear as two stars. Finer detail on the moon and planets will also be visible through the large instrument. This quality of bringing out finer details or separating close stars is called *resolving power*.

The largest refracting telescope has a lens of 102 cm (40 inches) diameter and is the principal instrument of the Yerkes Observatory at Williams Bay, Wis. It will separate two stars $0''.14$ apart.

64. The Eye-piece.—Two general types of eye-pieces are in use—the positive and negative. Each has certain advantages and certain disadvantages.

The Positive Eye-piece.—This consists of two plano-convex lenses mounted in a tube which is usually made of brass (Fig. 42). This type gives a very flat field of view but is not achromatic. In using this eye-piece the image is a short distance in front of the larger lens.

FIG. 41.—The great refracting telescope of the Lick Observatory, Mt. Hamilton, California. Diameter of lens 91 cm (36 inches); focal length, 17.7 meters (58 feet).

The Negative Eye-piece.—This type is essentially achromatic but does not give so flat a field of view as the positive (Fig. 42). When using this eye-piece the image falls between the two lenses.

Other and more complicated eye-pieces have been devised, but as they are more expensive they are not in such general use.

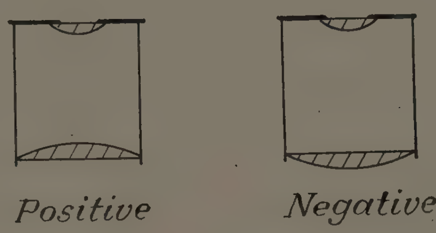


FIG. 42.—Eye-pieces.

65. Magnifying Power of a Telescope.—The magnification of a telescope is defined as the number of times the diameter of an object is apparently increased when looked at through the telescope as compared with the diameter when seen with the unaided eye. Thus, suppose a planet has an apparent angular diameter of 1′ as seen by the naked eye. A magnification of 60 would make the apparent diameter 1°, or double the apparent diameter of the moon, while a magnification of 120 would make the apparent diameter in the telescope 2°, etc.

The magnification of a telescope depends upon the relation between the focal lengths of objective and eye-piece according to the equation

$$M = \frac{F}{f},$$

where M is the magnifying power, F the focal length of the objective and f the focal length of the eye-piece.

The focal length of the eye-piece depends primarily upon the curvature of the lenses used, and is defined as the focal length of a single lens having the same magnification. If we desire to use various magnifying powers with any objective it is only necessary to have a set of eye-pieces of different focal lengths. For small telescopes two or three eye-pieces are usually sufficient, but large telescopes may require a dozen or more if the instrument is to be used effectively.

The best magnification to use depends upon the object being studied and upon the steadiness of the atmosphere. Bright objects can be magnified more than faint ones, but the steadiness of the air plays the most important rôle. When the atmosphere is unsteady the image shows tremors. Since the tremors are magnified as well as the image as a whole, it is possible to use too great a magnification and therefore actually to see less than with a lower power. Even under the best conditions it is seldom

advantageous to use a power exceeding 20 to the centimeter (50 to the inch) of aperture of the objective.

66. The Photographic Refractor.—Thus far we have considered the refracting telescope as a visual instrument. The eye is most sensitive to yellow and green light and these two colors are brought to the same focus by the lens combination. Lenses of this sort are not properly focused for the blue and violet light, which is most effective on the ordinary photographic plate, and therefore they cannot be used directly for the photography of celestial bodies.

Fig. 43.—A simple equatorial mounting.

Two methods have been employed to change the visual refractor into a photographic instrument. The simplest method is to use a special light filter which absorbs the blue and violet light and allows only the yellow and green to pass. Such a filter, when used with photographic plates sensitive to yellow and green light, will give excellent results except that much longer exposures must be given than if blue light were used.

Another method is to add a third lens, which can be placed in front of the visual objective and thus bring to a focus the blue and the violet light.

When a refractor is to be used exclusively for photographic work the lens is made to focus the blue and the violet light. Such a telescope is known as a *photographic refractor*. It cannot

be used for visual observations and it is necessary to employ a visual telescope mounted parallel to it for guiding purposes.

67. The Telescope Mounting.—Except for very small instruments the best form of mounting is the equatorial type (Fig. 43). In this form the main axis is set parallel to the earth's axis and the other at right angles to it. These are called the *polar axis* and *declination axis* respectively (see also Fig. 41).

With a telescope mounted in this way it is necessary to turn only the polar axis in order to follow an object across the sky. All larger telescopes are equipped with a driving mechanism (usually actuated by a weight) which turns the polar axis at just the rate necessary to counteract the earth's rotation and thus follow an object in the sky as long as may be desired.

THE REFLECTING TELESCOPE

68. The earliest telescopes were all refractors, but they seldom exceeded a few inches in diameter because of the impossibility of obtaining good optical glass in large discs and because chromatic and spherical aberration were so annoying in instruments of any size. Dollond's success in making achromatic objectives eliminated the serious aberration difficulties but the lack of optical glass discs of any size was for many years an unsurmountable barrier.

Before Dollond's time Newton had developed the reflecting telescope, one of these instruments being presented by him to the Royal Society in 1671.

69. Principle of Reflecting Telescope.—If a parallel beam of light is allowed to fall on a parabolic reflecting surface, as indicated in Fig. 44, the rays of light are brought to a focus at a point F. Hence for distant objects such a reflecting surface will form an image of the object at the focus by reflection just as a convergent lens will form an image of an object by refraction.

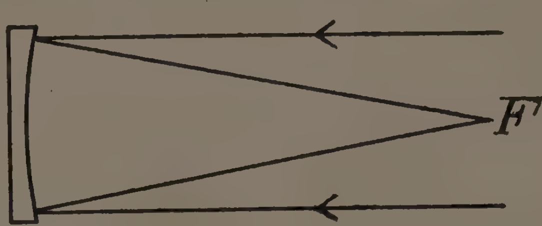


Fig. 44.

The mirrors of the early reflectors were made of speculum metal (an alloy consisting mostly of copper and tin), but the modern ones are made of glass, the reflecting surface being coated with a thin film of silver. The reflection is directly from the silver surface, the light not entering the glass at all.

The only purpose served by the glass is that of a rigid form for the silver film.

70. Types of Reflecting Telescopes.—Since the image formed by the reflector is in the axis of the mirror and on the same side as the object, it is not in a convenient position for observation. Two methods are in general use to obviate the difficulty. The first is to insert a small plane mirror into the converging beam before it comes to a focus and reflect the light to the side of the tube so that the image is formed at F (Fig. 45a). The second method is to place a convex mirror near the upper end of the tube and reflect the beam downward through a hole in the large mirror as shown in Fig. 45b. If it is not advisable to cut an opening through the large mirror a small plane mirror may be placed

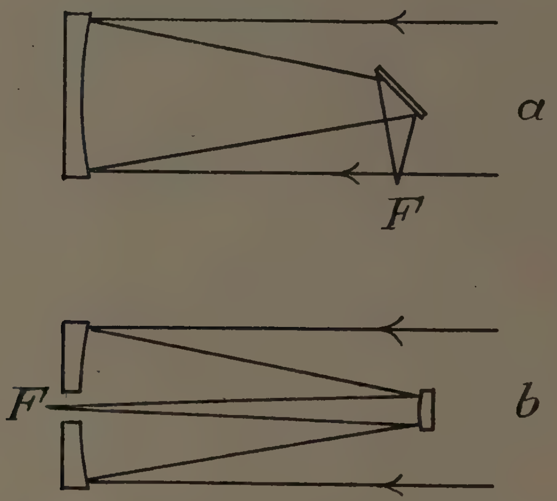


Fig. 45.—The two common types of reflecting telescopes: *a*. Newtonian type; *b*. Cassegrainian type.

just in front of it and the image formed at the side of the tube close to the lower end.

The first type was devised by Newton and the second by Cassegrain. The Cassegrainian form has the advantage over the Newtonian that by using different convex mirrors the size of the image can be varied within wide limits. Other types have been devised but are not now in general use.

The introduction of a small additional mirror in the path of the incoming light reduces the light-gathering power of the instrument, but there is no way of avoiding this. Secondary mirrors are supported by thin metal strips extending inward from the main tube. These strips are the cause of the rays radiating from

the images of bright stars when the reflector is used for direct photography.

71. Relative Advantages of Refractors and Reflectors.—In order to correct a telescope lens for spherical aberration it is necessary to have the focal length about 15 times the diameter of

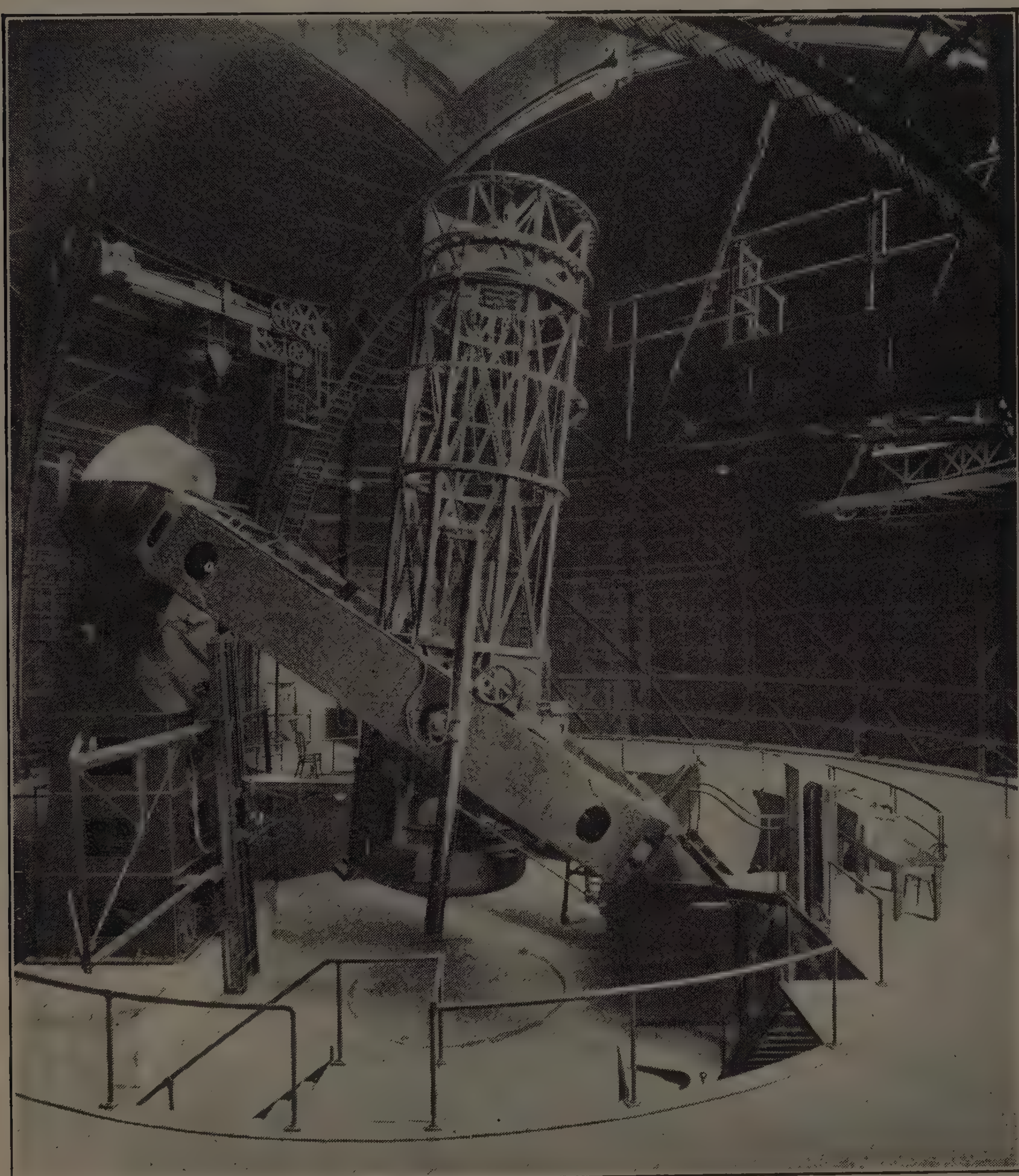


FIG. 46.—The great 254-cm (100-inch) reflecting telescope of the Mt. Wilson Observatory, Mt. Wilson, California.

the lens (this number is called the focal ratio). The great Lick and Yerkes refractors have focal ratios of nearly 20, but some smaller instruments have been constructed in which this ratio is as low as 10. The reflector, however, may be constructed with almost any focal ratio from 4 upward. The large modern

reflectors, such as the 254-cm (100-inch) of the Mt. Wilson Observatory, and the 183-cm (72-inch) of the Dominion Astrophysical Observatory, have ratios of about 5. Thus the refractor is about three times as long as a reflector of the same aperture. This is of considerable importance when considering the cost of the dome for the instrument.

FIG. 47.—The 183-cm (72-inch) reflecting telescope of the Dominion Astrophysical Observatory, Victoria, B. C.

The mirror has but one surface which must be brought to the proper curvature, while the lens has four. The cost is therefore much less.

A much poorer quality of glass can be used for the mirror than for the lens, as the light does not reach the glass of the mirror at all.

The mirror is perfectly achromatic, while no lens can be wholly so. The reflector may therefore be used for both visual and photographic observations without change.

The light-gathering power of the reflector is less than that of the refractor for apertures of 80 to 100 cm (30 to 40 inches) or less. For larger instruments the reflector is superior to the refractor. This is due in the smaller instruments to the interception of light by the secondary mirror. For larger instruments the increasing thickness of the lens increases the absorption of light and the loss by absorption is greater than the loss due to the secondary mirror of the reflector.

A mirror must be resilvered about twice a year to keep it up to its greatest efficiency, and it is also much more sensitive to changes of temperature than a lens.

At the present time the reflector dominates the field for large instruments, but the refractor is still the favorite for apertures of 50 cm (20 inches) or less.

THE SPECTROSCOPE

In the modern observatory the spectroscope is second only to the telescope in importance as an astronomical instrument of research. It has unlocked many doors which appeared forever closed to the astronomer of 100 years ago and many results have been achieved of which he had not even dreamed.

72. Principle of the Spectroscope.—The instrument consists of three parts: the collimator, the prism and the view-telescope (Fig. 48).

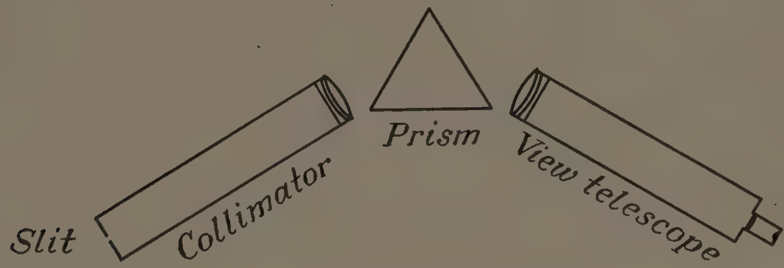


FIG. 48.—The spectroscope.

The Collimator.—A narrow slit with movable slit jaws is placed at the focus of an achromatic lens. Light entering the slit and passing through the lens is therefore sent into the prism as a parallel beam.

The Prism.—The purpose of the prism is to analyze the light coming from the collimator so that the light of the various wave-

lengths is separated. If greater dispersion is desired, more than one prism may be used. For very high dispersion a diffraction grating is used in place of a train of prisms. For the theory of the grating the student is referred to any standard text on physics.

The View-telescope.—The lens of the telescope brings the dispersed beam of light to a focus, where it is examined through the eye-piece. This dispersed beam as seen in the telescope is called a *spectrum.*[1]

If the slit is illuminated by monochromatic light there appears in the eye-piece a line of light of the same color as passed through the slit. This line is an image of the slit.[2]

73. Bright-line Spectra.—If light from a hydrogen or helium tube is examined by means of the spectroscope the spectrum is found to consist of a series of bright lines. Luminous metallic vapors behave likewise (Fig. 49, middle). No two chemical

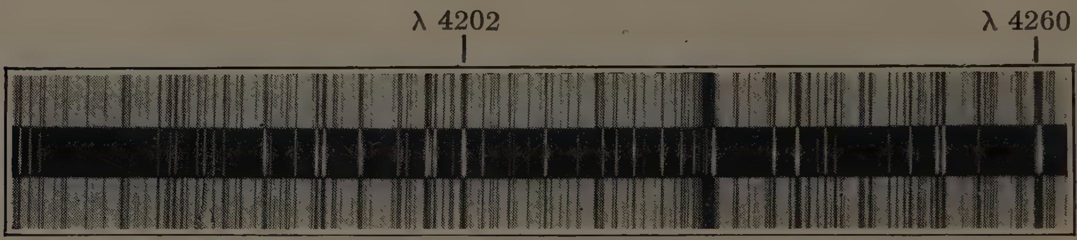


Fig. 49.—Portion of solar spectrum (top and bottom); spectrum of iron vapor (middle). (*Photographed at the Mt. Wilson Observatory.*)

elements have the same series of lines and no two lines in the spectra of any two elements have exactly the same wave-length. This principle, the first law of spectroscopy, may be stated as follows:

1. *The luminous gas or vapor of a chemical element, when under low pressure, gives a spectrum of bright lines and each element exhibits its own characteristic lines.*

This is what we might expect from the Bohr theory of the atom, since light waves are radiated only when an electron drops from an outer to an inner orbit. Since the charge on the nucleus is

[1] If the spectrum is to be photographed instead of being observed visually, the eye-piece is removed and a photographic plate placed at the focus of the telescope lens. This converts the view-telescope into a camera and the entire instrument is then called a *spectrograph.*

[2] It is very important that the student realize this point and it is desirable to perform experiments to demonstrate it by using small apertures of various shapes in place of the ordinary slit.

different for each element, the electron orbits will be differently spaced and hence no jumps of electrons in different atoms will be exactly alike.

Low pressure is specified, since only at low pressures are the atoms of a gas sufficiently far apart to allow each one to act more or less independently.

74. Continuous Spectra.—In Sec. 54 it was found that white light consisted of waves of all lengths from red to violet. Examination of white light with a spectroscope will therefore show a continuous band of color, running without interruption through red, orange, yellow, green, blue and violet. Such a spectrum is called a *continuous spectrum.* Since white light can be obtained from an incandescent solid or liquid, or from a luminous gas under high pressure, the second law is as follows:

2. *An incandescent solid or liquid, or a luminous gas under high pressure, produces a continuous spectrum.*

We would also expect such a result, for when atoms are closely packed there must be great interference with the freedom of motion of the electrons, so that jumps of all sorts might be expected and thus light of all wave-lengths emitted.

75. Absorption Spectra.—If light from a source giving a continuous spectrum is allowed to pass through a cooler gas at low pressure the cooler gas will absorb some of the energy from the continuous radiation. The absorption, however, is not general, but is primarily of those light-waves having the frequency which the atoms of the cooler gas have when they act as radiators of energy themselves. Under these conditions there will be gaps in the continuous spectrum, the gaps falling at precisely those places where we would find bright lines if the cooler gas were giving a spectrum of bright lines. Such a spectrum with gaps or dark lines is called an *absorption* spectrum (Fig. 49). The third law is as follows:

3. *If light from a source of continuous radiation passes through a cooler gas under low pressure it loses energy of precisely those wave-lengths which the gas itself would emit if radiating alone.*

Absorption of energy in this case may be more or less analogous to the phenomenon known as sympathetic vibration in sound.

76. The Comparison Spectrum.—In order to determine whether a certain element is present in a heavenly body, a simple device is used. In front of the slit of the spectroscope two small total-reflection prisms are placed so that light from a known

source may be sent into the spectroscope as at *a* and *c* (Fig. 50), while the light from the heavenly body is sent through the slit at *b*, or *vice versa*. If some of the lines in the spectrum of the heavenly body agree in position with lines from the known source we have the proof that the known substance is to be found in the heavenly body (see Fig. 49, which compares the spectrum of the sun with that of iron). The spectrum of the known substance is called a *comparison spectrum.*

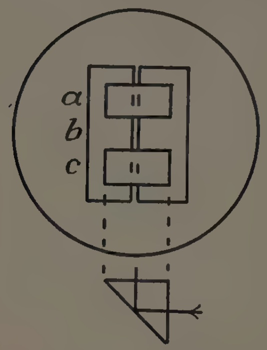


FIG. 50.—Prisms for comparison spectrum in front of slit of spectrograph.

77. Doppler's Principle.—A passenger on a train passing a crossing bell may note a drop in the pitch of the sound from the bell—the greater the speed of the train the greater the change in pitch. This phenomenon may be explained by a diagram (Fig. 51).

The pitch of the bell is determined by the number of sound waves reaching the observer per second. If the observer is stationary at *a*, as many sound waves will strike his ear as the bell emits per second. If the observer moves toward the bell a distance *ab* in 1 second, then not only will all the waves passing *a* strike his ear but also one more, the wave *ab*. The pitch of the bell will therefore be higher than if the observer had remained at rest.

FIG. 51.—Doppler's principle applied to a crossing bell.

Again, suppose the observer at rest at *c*. He will hear the sound of the same pitch as when at rest at *a*, for the same number of sound waves will reach his ear at the one place as at the other. Let him now move from *c* to *d* in 1 second. It is evident that the wave *cd*, which would have passed him had he remained at *c*, has not yet done so. One less wave has reached him and the pitch of the bell will be lower.

Summarizing this in a different way, we may say that when an observer approaches a source of sound the observed wave-length of the sound (as indicated by the pitch) is decreased, while when he recedes from the source the observed wave-length is increased.

It is evident that the amount of the change in observed wave-length depends upon the velocity of the observer and is proportional to his velocity. This can be expressed in the form of a proportion as follows:

$$\frac{v}{V} = \frac{\Delta\lambda}{\lambda},$$

where v is the velocity of the observer, V the velocity of sound, $\Delta\lambda$ the change in wave-length and λ the wave-length for an observer at rest. Solving the equation for v, we have

$$v = \frac{V \times \Delta\lambda}{\lambda},$$

a formula which will allow us to determine the velocity of the observer if we know the velocity of sound, the change in wave-length and the wave-length of the sound for the observer at rest.

As early as 1845 Buys-Ballot made some experiments in Holland, using locomotives to carry sounding bodies, and found good agreement between theory and experiment.

This principle of change of wave-length with velocity is known as *Doppler's principle.*

78. Doppler's Principle Applied to Light.—The same considerations which have been applied to sound can be applied to light. If the distance between a source of light and an observer is decreasing the wave-lengths of the lines of its spectrum will be decreased, while if the distance between source and observer is increasing the wave-lengths of the lines in its spectrum will be increased. We may state this as follows:

If the distance between an observer and a source of light is increasing the lines in the spectrum of the source are displaced toward the red, while if the distance is decreasing the lines of the spectrum are displaced toward the violet, the displacement being proportional to the velocity.

Examples illustrating this principle will be found in Secs. 380 and 381.

OTHER INSTRUMENTS

79. The Transit Instrument.—The transit instrument is used for the determination of time by observing stars as they cross the meridian. The lens is usually from 5 to 10 cm (2 to 4 inches) in diameter. The telescope is rigidly attached to a stiff horizontal axis, which is placed in an east-west direction, so that the

instrument is always pointing to the meridian as it rotates on the axis. Figure 52 shows such an instrument.

In the field of view of the eye-piece, at the focus of the objective, a series of spider threads or fine lines ruled on glass are placed. This is called the *reticle* (Fig. 53). The sidereal clock time when

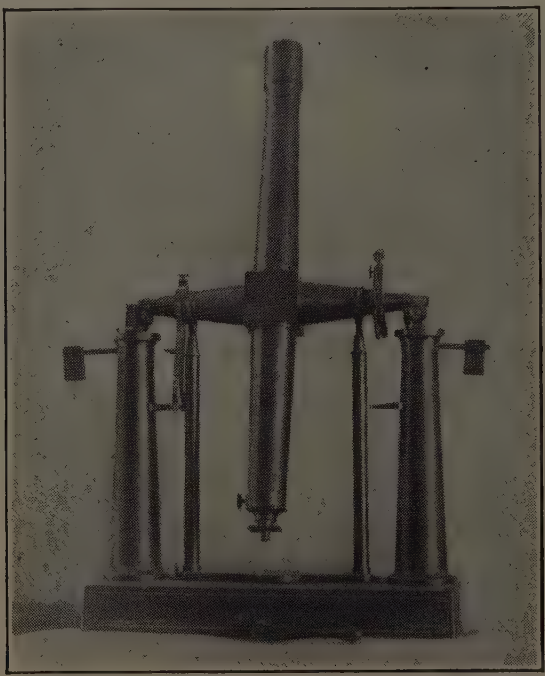


Fig. 52.—A simple transit instrument.

a star crosses each thread is noted and the average taken as the time when it was in the center of the field. If the instrument is in exact adjustment this will be the clock time when the star is on the meridian. Since the right ascension of the star is known from the catalog, the difference between the observed clock time and the right ascension will be the amount by which the clock is in error. The *clock correction* is the quantity which must be *added* to the clock reading to give the correct time.

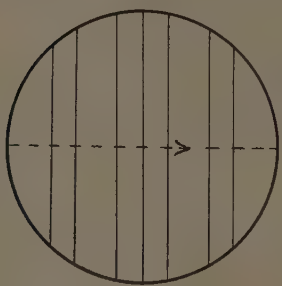


Fig. 53.—Diagram of reticle of transit instrument.

No transit instrument can be kept in exact adjustment in the meridian. Changes of temperature, etc., produce minute changes in the level and direction of the horizontal axis and in the direction of the line of sight with respect to the axis. The amount of these errors must be determined and allowed for in exact time determinations.

80. The Meridian Circle.—This instrument (Fig. 54) is the same in principle as the transit instrument but is equipped with

carefully graduated circles and various devices for refined measurements, so that in addition to observing meridian transits of stars it is also possible to determine their declinations. It is usually a larger instrument than the transit, the lens having a diameter of from 12 to 23 cm (5 to 9 inches).

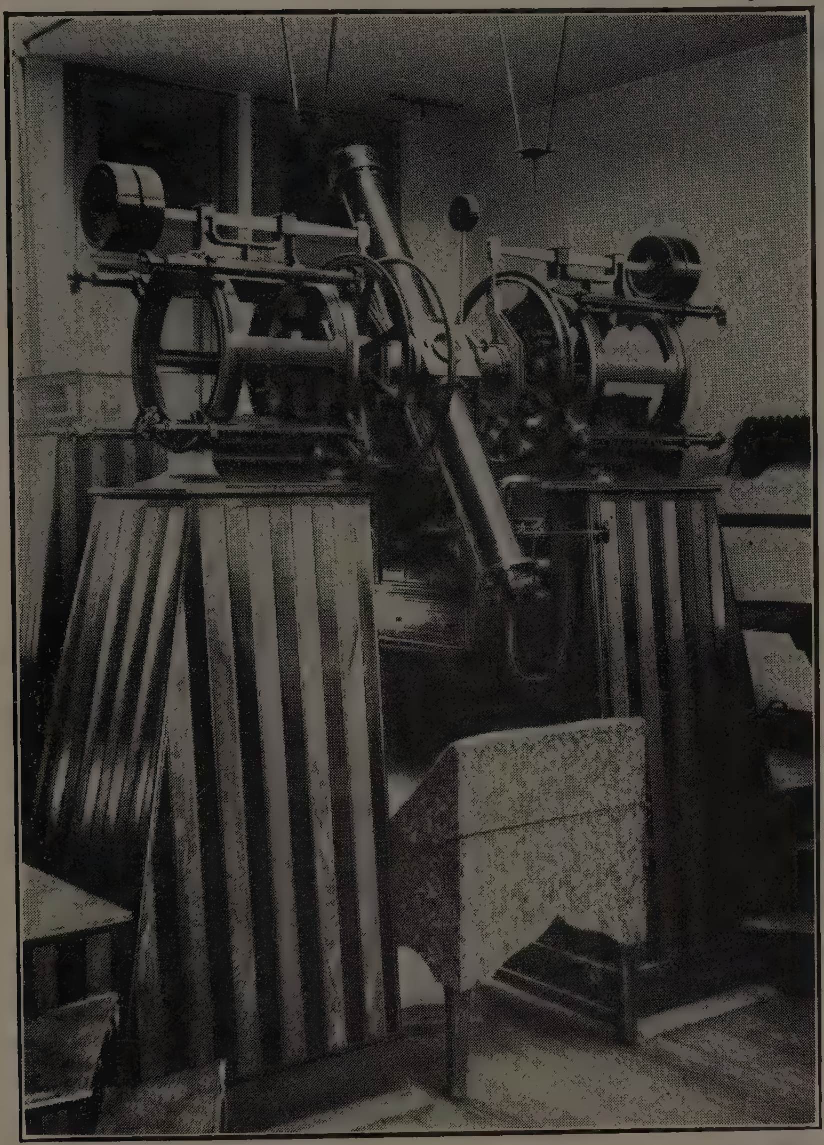


FIG. 54.—The 12-cm (5-inch) meridian circle of the Goodsell Observatory, Carleton College.

81. The Chronograph.—For the purpose of accurately recording the clock times of various observations an instrument called a chronograph is used (Fig. 55). This consists of a cylinder about 35 cm (14 inches) long and 15 cm (6 inches) in diameter which rotates once per minute. A sheet of paper is wound around the cylinder and held by clips. In front of and parallel to the cylinder is a long screw which drives a small carriage. This

carriage carries an electromagnet with a fountain pen attached to the armature of the magnet by means of a short lever. As the cylinder revolves the pen traces a line on the paper, and, since the pen is also being moved forward slowly by the screw, the line becomes a helix.

In the circuit of the electromagnet are placed a clock and a signal key. Every even-numbered second the circuit is broken

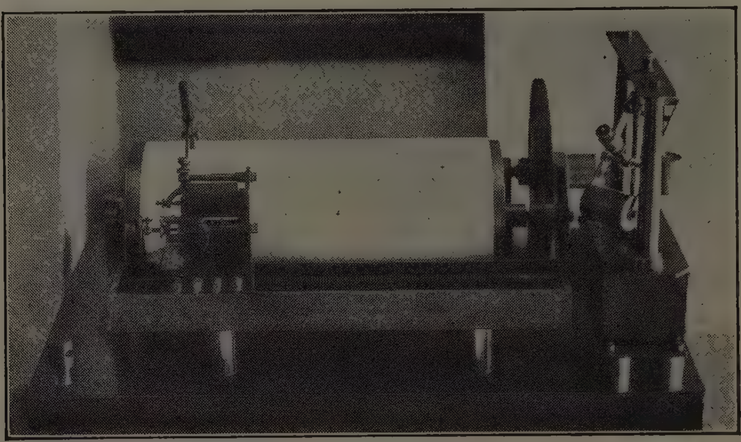


Fig. 55.—A chronograph.

for an instant by the clock, so that the pen makes a slight jog in the line. By means of a device in the clock there is some way of indicating the end of each minute, either by omitting the break of the circuit at 58^s or by including one at 59^s as well. By this means definite minutes and seconds can be identified on the chronograph sheet.

Figure 56 shows a small portion of a chronograph record. In addition to the jogs caused by the clock the observer may press

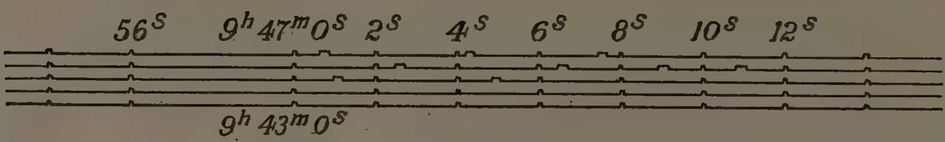


Fig. 56.—A portion of a chronograph record.

his signal key whenever he wishes to make a signal. This makes additional jogs on the line, whose time can then be read from the sheet by means of a suitable scale to about one one-hundredth of a second.

As the observer is watching a star cross the field of view of the transit instrument he will press the key each time the star crosses

one of the spider threads of the reticle. When his observations are completed he then reads off the clock times of the star transits of the threads.

Another type of chronograph, called the *printing chronograph*, has been developed which prints on a strip of paper the times when the key is pressed. It is much more convenient than the type described but has not come into general use because of its much greater cost.

82. The Astronomical Clock.—The astronomical clock is nothing more than a very fine clock with a seconds pendulum and a device for automatically making or breaking an electric circuit either each second or every 2 seconds, usually the latter. The dial is graduated to read 24 hours instead of 12 hours, so that there is no chance of misreading the time of day.

The best clocks, however, are still subject to a change of rate with changes of temperature which affect the length of the pendulum, and by changes in barometric pressure which affect the resistance of the air to the movement of the pendulum. In order to prevent changes in the length of the pendulum with changes of temperature the rod is made of invar, an alloy of nickel and steel whose expansion coefficient is only about one one-hundredth that of steel, and the clock is placed in a room whose temperature is kept as nearly constant as possible by means of a thermostat and some source of heat. The varying barometric pressures are also avoided by sealing the clock in an air-tight case and partially exhausting the air.

A clock of this character cannot be wound by ordinary means and so an automatic electrical winding device is provided. By means of this a small weight of about 15 grams (½ ounce) is raised a short distance every 30 to 40 seconds. The weight drives the clock as it falls.

No clock is perfect and none will keep absolutely correct time. The best that is hoped for is that it will gain or lose by a definite amount each day. This amount of gain or loss is called the *daily rate* of the clock. A clock whose daily rate can be depended upon to one or two hundredths of a second is of exceptionally fine quality.

The master clock or clocks of an observatory are usually not set except when they are cleaned and oiled. This is done once in two or three years. The clock corrections are determined by the transit and chronograph and a record kept. By combining

the last-determined clock correction with the daily rate the correct time at any instant can be obtained.

Clocks other than the master clock are compared with the latter and may be set daily so as to show correct time. Such secondary clocks need not be of the highest quality.

83. The Micrometer.—The micrometer is a device used in connection with a meridian circle or equatorially mounted telescope to measure the angular distance between two objects in the field of view of the eye-piece. Several kinds of micrometers have been devised, but the only one now in general use is known as the filar (or thread) micrometer (Fig. 57).

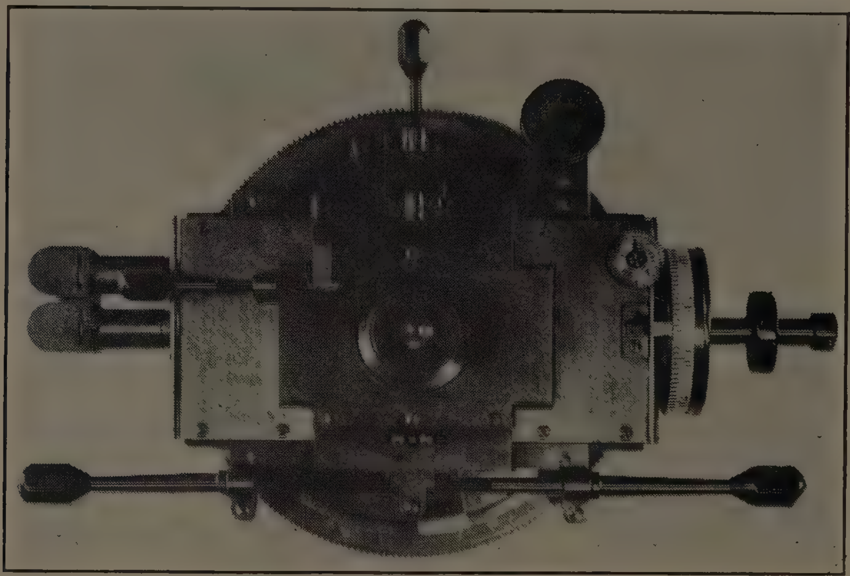


Fig. 57.—A filar micrometer.

In its simplest form it consists of two parallel spider threads, one fixed and the other movable. The motion of the latter is controlled by a finely made screw with a graduated head and a device for counting the number of revolutions of the screw. By suitable methods the exact angular distance which the movable thread traverses with one turn of the screw can be determined. This may be of almost any value from 10″ upward. Besides the motion of one thread with respect to the other, both may be rotated about the line of sight of the telescope so that they may be set at any angle with respect to a north-and-south line in the sky.

If it is desired to measure the distance between a comet and a star whose position is known the threads are first rotated until they are either exactly north and south or east and west. A

reading of the graduated head of the screw is taken when both threads[1] are in coincidence. The star is then placed on the fixed thread and the movable thread set on the comet (Fig. 58). By again reading the screw head the number of revolutions and a fraction of the screw through which the thread was moved is

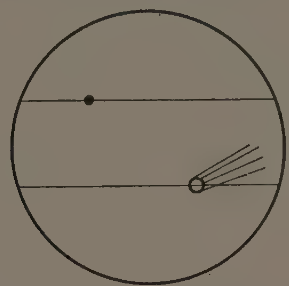


FIG. 58.—The use of the filar micrometer.

obtained. When this is multiplied by the angular value of one revolution the angular distance between star and comet in a north-south or east-west direction is obtained.

The filar micrometer is usually limited to measuring small distances, as both objects must be in the field of view at the same time.

[1] The threads of a micrometer are often called *wires*.

CHAPTER VI

THE MOON

The moon must have been one of the first of the heavenly bodies to engage the attention of primitive man. The various phases shown in the course of the month; its movement among the stars; its disappearance near the western side of the sun followed by its reappearance, a few days later, on the eastern side; the dark spots to be seen on its surface—all these gave rise to thought which resulted in various ingenious theories to account for them. Even to-day the moon is an object of interest, both from the popular and from the scientific point of view.

84. Distance.—The moon is the nearest of the heavenly bodies. Its mean distance from the earth is 384,400 km (238,860 miles), but, on account of the eccentricity (Sec. 128) of its orbit, and the perturbations (Sec. 131) to which it is subjected, its actual distance varies from about 357,000 km (222,000 miles) to about 407,000 km (253,000 miles).

85. The Moon's Orbit.—The orbit of the moon is an ellipse which has an eccentricity of 0.055. The plane of the orbit is inclined to the plane of the ecliptic at an angle whose average value is 5° 9′. This inclination varies about 12′ either way from the mean value. The line of apsides (longest diameter) makes one revolution from west to east in about 9 years, while the line of nodes (the line of intersection of the plane of the moon's orbit with the plane of the ecliptic) moves from east to west and completes one revolution in about 19 years. These motions of the line of apsides and line of nodes are caused by perturbations or disturbances of the moon's motion by the sun.

86. Diameter, Mass, Etc.—The moon's apparent outline is circular and its angular diameter at mean distance is 31′ 5″. Its linear diameter is 3476 km (2160 miles). Its mass is approximately 0.0123 times that of the earth and its mean density is 3.4 times that of water. The force of gravity at its surface is one-sixth that on the earth, that is, a man who weighs 180 pounds on the earth would weigh but 30 pounds on the moon. If we

could make a trip to the moon and live there for a time this low value of gravity would lead to many interesting experiences.

87. The Phases of the Moon.—We see the moon because of the sunlight falling on it. The side of the moon turned toward the sun is illuminated while the other side is in darkness. Because of the orbital motions of moon and earth the relative positions of sun, moon and earth are constantly changing. When the moon is on the opposite side of the earth from the sun we say it is *full*, while when it is in line with the sun it is *new*. Figure 59 illustrates these and other phases.

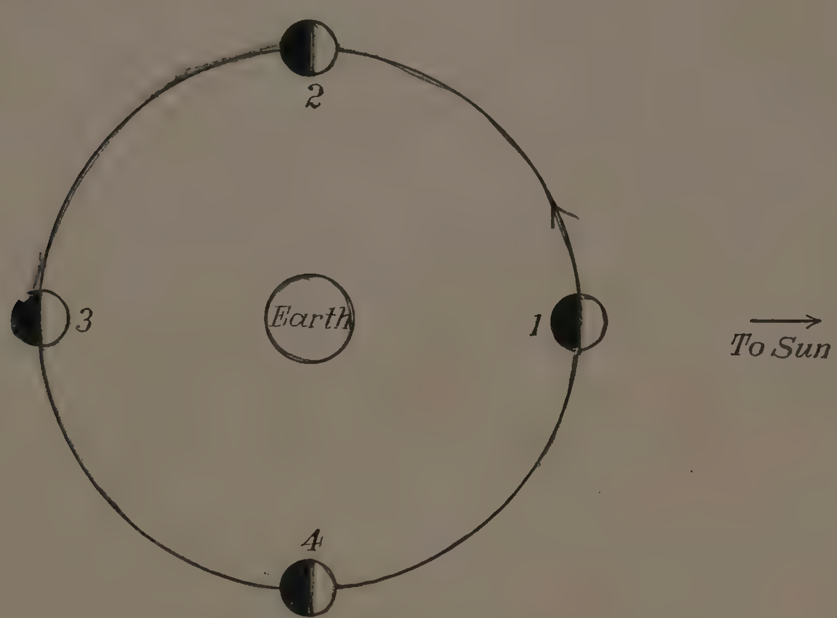


FIG. 59.—The phases of the moon.

Since we can see only that portion of the moon which faces the earth, it is evident that when in position 1 we cannot see it at all. When in position 2 we see half the surface illuminated, while between positions 1 and 2 we see the crescent phase. Between positions 2 and 3 we see more than half the surface illuminated. This is termed the *gibbous* phase. In position 3 the entire side turned toward the earth is illuminated and we have full moon. From position 3 to positions 4 and 1 we see the illuminated surface gradually diminish until it vanishes at 1. When the moon is in positions 2 and 4, so that we see half of it, the phases are called *first* and *third quarters* respectively.

The line which separates the illuminated from the unilluminated portion is called the *terminator*. The apparent edge of a heavenly body is often called the *limb*.

88. The Sidereal Month.—If observed from night to night it will be seen that the moon moves eastward among the stars so that in a month it completes a circuit of the heavens. The *sidereal month* is defined as the time it takes the moon to make one revolution about the earth with reference to the stars, that is, the time required to move around the sky from any particular star until it again reaches it. The sidereal month has a length of $27^d\ 7^h\ 43^m\ 11^s.5$.

89. The Synodic Month.—From ancient times the meaning of the term "month" has been the interval of time from new moon to new moon or from full moon to full moon. This month is called the *synodic month* and its length is $29^d\ 12^h\ 44^m\ 2^s.8$. The diagram (Fig. 60) shows why the synodic month is longer than the sidereal month.

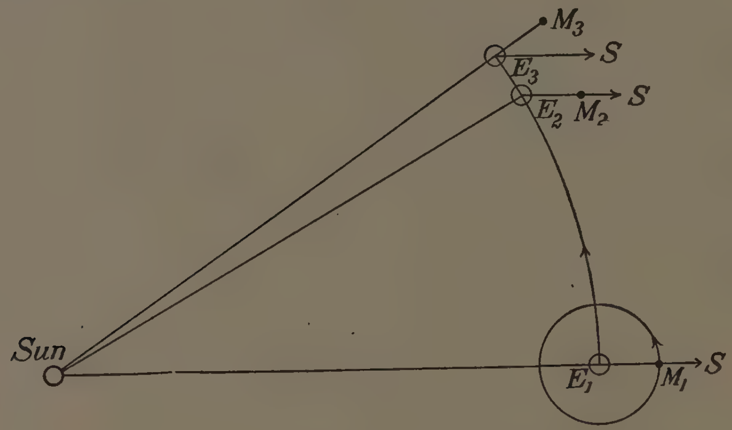


FIG. 60.—Relation of synodic and sidereal months.

Let us assume that at the time of full moon the moon is in line with a star in the direction E_1M_1S. After an interval of one sidereal month the earth will be at E_2, the moon at M_2, and the line E_2M_2S will be parallel to E_1M_1S. The moon will, therefore, be in line with the same star again but, since it is not yet opposite the sun, it is not full. In order to have full moon the moon must move forward until the line Sun-Earth, when continued, will strike the moon. In the meantime the earth is also moving forward to a new position E_3, so that the synodic month is not completed until the line *Sun*-E_3M_3 is a straight line. The additional time required for the moon to move through the angle M_3E_3S is the interval of over two days by which the length of the synodic month exceeds the sidereal.

90. Earth-shine on the Moon.—Shortly after new moon we may see the crescent moon brightly illuminated by the sun while

the remainder of the surface is seen illuminated by a faint light. This appearance is most marked when the crescent is narrow and it gradually becomes less noticeable until by the time the moon has reached first quarter it disappears. The faint illumination is caused by sunlight reflected to the moon from the earth and then reflected back again to the earth. It is called *earth-shine.* Similar effects may be seen between last quarter and new moon.

91. Rotation.—The moon has a slow rotation about an axis which is tipped about 6°.5 from the perpendicular to the plane of its orbit. A remarkable feature of this rotation is that its period is exactly equal to its sidereal period of revolution and is also in the same direction. In consequence, the moon always turns the same face toward the earth.

The reason for this is not wholly clear, but it is probably due to tides raised in the body of the moon at a time when it may have been in a more or less plastic condition. The friction of these tides finally produced the effect. This explanation of the phenomenon is the best one available and appears sufficient if we grant that the moon was ever plastic.

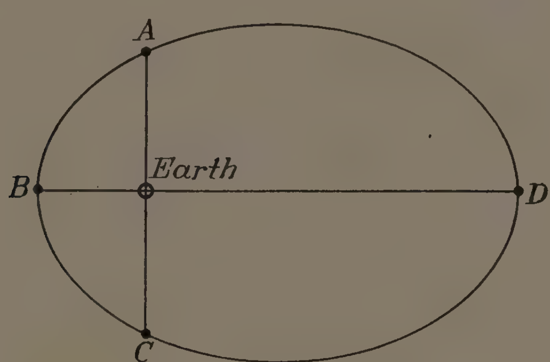


FIG. 61.—Libration in longitude.

92. Libration.—Because the moon's axis is not perpendicular to the plane of its orbit we are able to see past the one pole for half of the month and past the other pole during the other half. The maximum amount we may see past either pole on this account is about 6°.5 of latitude on the moon. This is called the *libration in latitude.*

Another libration, known as the *libration in longitude,* is caused by the fact that, while the rate of axial rotation is constant, the velocity in the elliptical orbit is not constant. This may be understood by reference to the diagram (Fig. 61). The moon moves more rapidly in the part of its orbit *ABC* than in the part

CDA. It therefore requires less time to move through the first 180° in the sky than through the second. Since its axial rotation, however, is at a constant rate, it will rotate less than half in the part *ABC* and more than half in the part *CDA*. The rotation will therefore be behind the orbital movement for part of the month and ahead in the other part. We may therefore sometimes see a little farther around the eastern side and at other times a little farther around the western side. The maximum value is nearly 8° of the moon's longitude.

A third libration of small amount has also been detected. There is some evidence that the moon is slightly elongated in the direction toward the earth. This third libration is due to a small pendulum-like oscillation of the body of the moon, and is known as the *physical libration*.

Other slight effects are due to our making observations from the earth's surface instead of from its center. The combined result of all librations is that we always have 41 per cent of the moon's surface turned toward us, a corresponding 41 per cent we never see, and of the remaining 18 per cent one-half will be turned toward us at any one time.

93. The Moon Day.—The length of the day on the moon is equal to the synodic month and not the sidereal month as is sometimes stated. A consideration of the geometry of the situation in connection with Fig. 60 will make this clear.

94. Occultations.—In her movement around the earth the moon necessarily passes between us and the stars. When this occurs for any particular star it is said to be occulted by the moon. The occultation of a bright star, especially when it takes place at the dark limb of the moon, makes an interesting observation. The star, shining in full brightness, is suddenly blotted out. The suddenness of the occurrence is almost startling. Later the star reappears on the other side of the moon, the time between disappearance and reappearance being about an hour if the occultation is approximately central.

Occultations have been used to determine the longitude of ships at sea, but this method has been superseded by more modern methods. The principal value of occultations at the present time lies in their use in determining the exact position of the moon among the stars.

Lists of stars to be occulted by the moon may be found in the *American Ephemeris* and in *Popular Astronomy*.

their center would see nothing of the mountains, as they would lie beyond his horizon (Fig. 64).

97. The Mountains.—These are found either as isolated peaks or in chains. Some of the chains are named after similar forma-

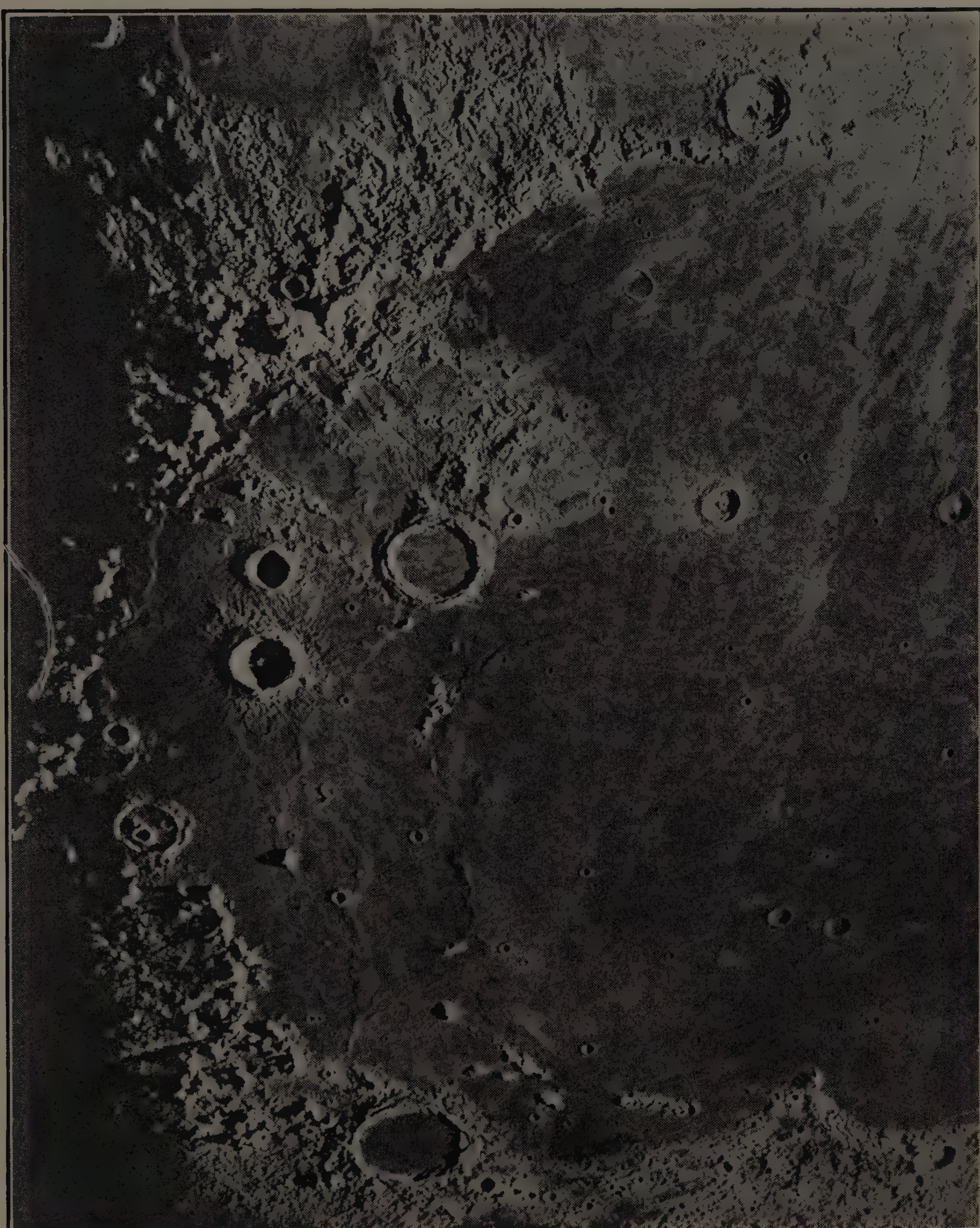


FIG. 64.—A great lunar plain, Mare Imbrium, and the surrounding chains of mountains. (*Photographed at the Mt. Wilson Observatory.*)

tions on the earth, such as the Alps, Caucasus and Apennines, while others are named after scientists, such as Leibnitz, Doerfel, etc.

The heights of the lunar mountains vary as do the heights of similar formations on the earth. Some peaks of the lunar Caucasus and Apennines rise to over 6000 meters (19,000 feet) in elevation, while in the great Leibnitz and Doerfel ranges elevations of 8000 meters (25,000 feet) and over occur.

98. Measuring the Height of Lunar Mountains.—One method of determining the height of a mountain on the moon is very simple in principle. The length of the shadow cast at any time by the mountain is measured by means of a micrometer (Sec. 83). From data supplied by the *American Ephemeris* the altitude of the sun as seen from the tip of the shadow at the time can be computed and the height of the mountain determined.

In Fig. 65, let CB be the height of the mountain, AB the length of the shadow and the angle A the altitude of the sun. The

Fig. 65.—Method of determining the height of a lunar mountain by means of its shadow.

distance AB will then be obtained from the micrometer measures and the angle A from the data of the *American Ephemeris*. Then by trigonometry,

$$CB = AB \tan A.$$

99. The Craters.—These formations bear a certain similarity to some volcanic craters on the earth, and hence the name. It must not be assumed that the name necessarily implies volcanic origin. Some observers have suggested names like *ring-planes* or *ring-mountains* for the larger craters.

There are many thousands of craters on the lunar surface, and these vary in size from mere pits less than ¼ km across to great ring-mountains like Copernicus (Fig. 67) or ring-plains like Clavius, having diameters of 90 and 225 km (56 and 140 miles), respectively. In the smaller ones we have simple depressions below the general surface, while in some of the larger ones the surrounding rim may rise to an elevation of over 5000 meters (16,000 feet) and individual peaks on the rim to even greater elevations. In some instances the floor of the crater is nearly at

the level of the rim, while in others it is considerably below the general level of the region outside.

There are usually secondary craters in the floor or slopes of the main formation, while in many instances a central peak or group of peaks rises from the floor.

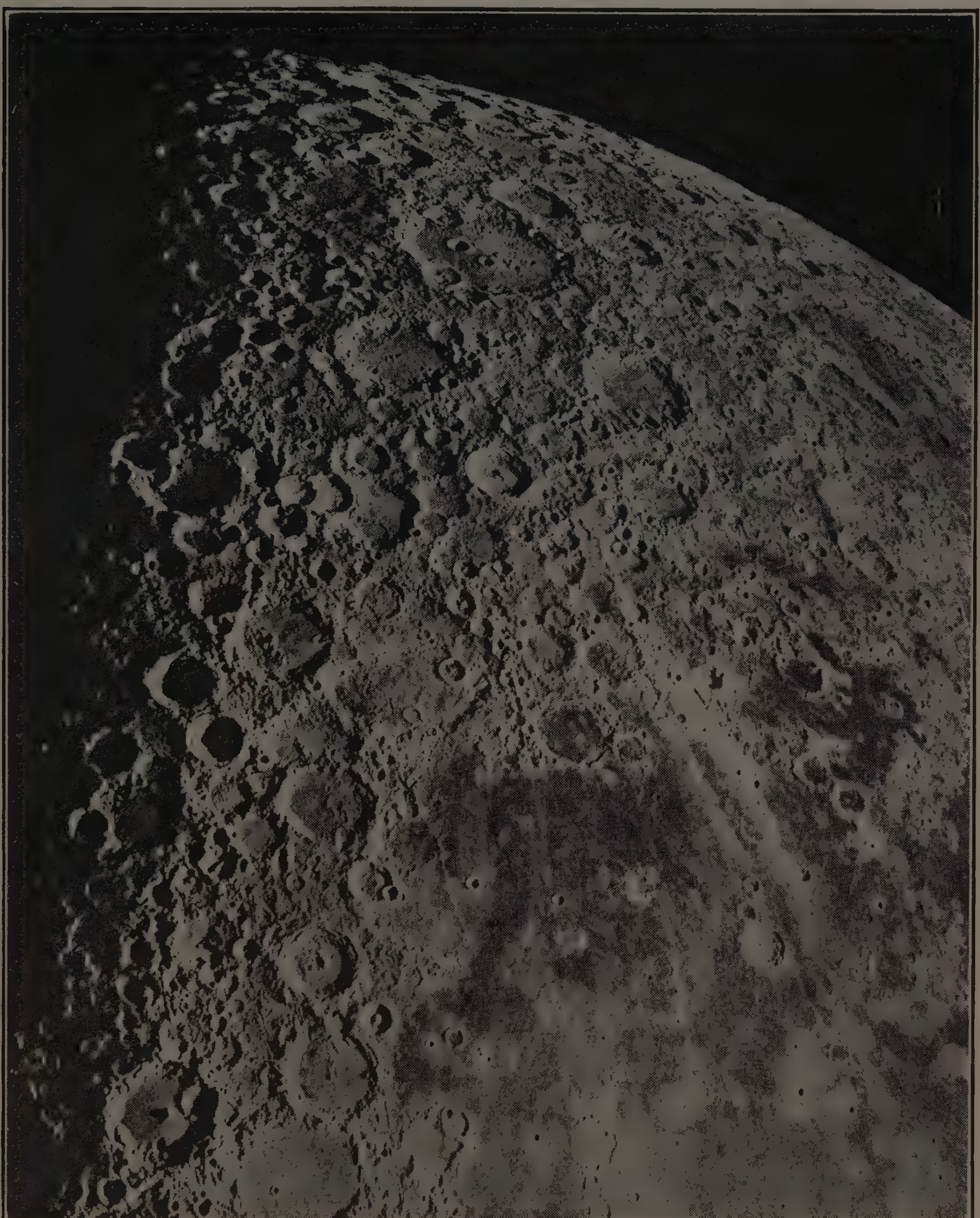


Fig. 66.—Lunar craters. (*Photographed at the Mt. Wilson Observatory.*)

100. Rills.—These are narrow, and usually deep, ravines or clefts which sometimes attain a length of from 300 to 500 km (200 to 300 miles). In some cases they intersect or branch and

they may cross mountain and plain without a break. In other cases their course is deflected by some formation or even interrupted, only to be resumed on the other side. Their real nature is uncertain but the idea that they were cracks which opened in the surface seems to be the simplest explanation.

101. Rays.—Around many of the larger craters there is to be seen a system of white streaks, in some cases with considerable interlacing while in others they extend almost directly away from a center, like spokes from the hub of a wheel. A good example

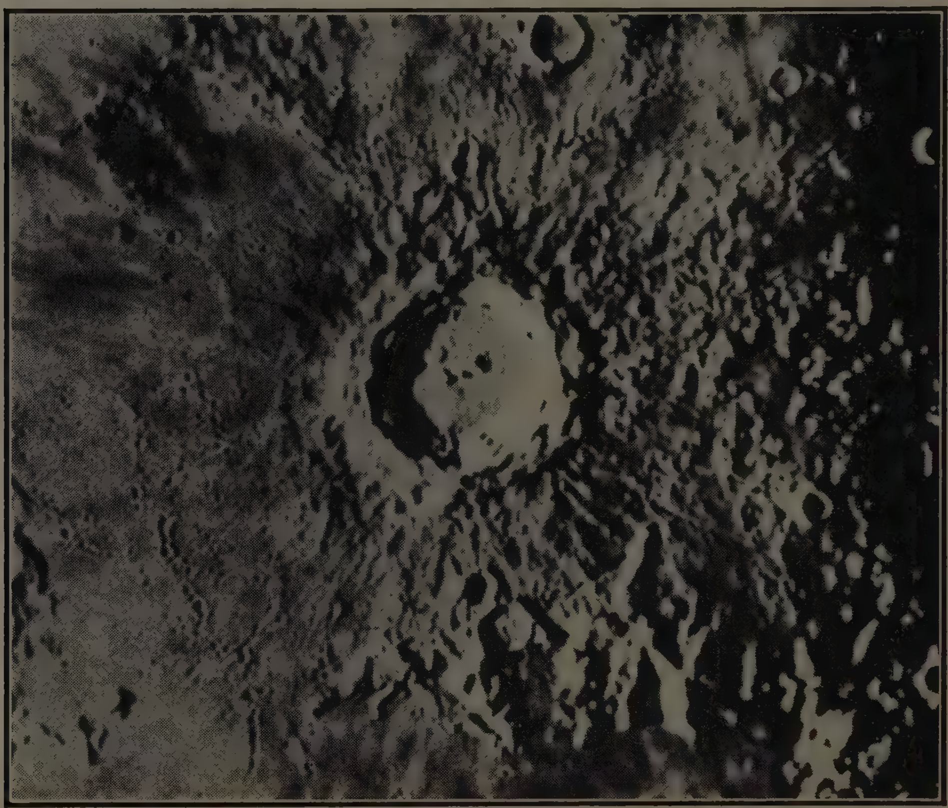


Fig. 67.—The lunar crater Copernicus. (*Photographed at the Yerkes Observatory, Williams Bay, Wis.*)

of the first kind is found around Copernicus, while the best example of the second is found around Tycho. In the latter case some rays can be traced nearly across the entire surface of the moon (Fig. 62).

The rays seem to be entirely a surface phenomenon and cross mountain, valley and plain without interruption. Apparently, they are white streaks on the surface itself and they are seen at their best when the sun is high for those regions on the moon.

102. Surface Materials.—We do not know of what materials the surface of the moon is composed. Observations by Wilsing

and Scheiner on the reflecting power of different parts in comparison with terrestrial rocks show that the dark surfaces of the lunar seas have the reflecting power of various lavas, while the bright parts of crater walls reflect as much light as volcanic ash.

The average *albedo*, or reflecting power, of the moon is low and determinations vary from 0.07 to 0.17. Russell's result is 0.073.

103. Origin of Surface Features.—There are two general lines of thought in this connection. The one assumes that the craters were caused by disturbances from without and the other that they can be explained by conditions formerly residing within the body of the moon.

The first we shall consider may be called the meteoric theory. This assumes that in the past the moon was subjected to bombardment by great meteors, which by impact on the lunar surface melted the material and while burying themselves threw up the surrounding wall. While it is impossible to assert that the theory is wholly wrong, yet there are some grave objections to it. In the first place, it would seem that many more meteors would strike the earth because of its larger mass than would strike the moon. The striking velocity would also be higher. As a result, it would seem as if the earth should show some evidence of such a bombardment, but none is known. In the second place, it seems necessary to show that an adequate source of meteors was available.

All other theories start on the assumption that the moon at some time in the past was a hot molten mass. Some of these theories then merely assume that the craters are great volcanoes built up on the moon's crust. Others require the action of tides in the body of the moon pushing up molten material from the interior and then allowing any unsolidified matter to drain away through holes in the crust. Another theory assumes heated gases from the interior bursting through the crust as great bubbles, the crust bulging up and then partially collapsing forming the rim of the crater.

It does not seem possible at the present time to decide definitely in favor of any particular theory, although it appears likely that some form of "molten moon" hypothesis is the more probable.

104. Temperature.—The temperature of the lunar surface is difficult to determine. It has been shown that a considerable part of the sun's heat which falls on the moon is first absorbed and then radiated and some observers have deduced temperatures

of over 100°C. (212°F.). This does not seem impossible, as the sun shines on a region for two full weeks without intermission. During the equally long two weeks' night, however, the temperature must fall very greatly, and from his observations Lord Rosse concluded that a difference of 300°C. (540°F.) between day and night temperatures is possible.

105. Atmosphere.—The moon possesses little or no atmosphere. The fact that there is no change in brightness between center and edge, the blackness of the shadows and the sudden disappearance of a star when occulted by the moon are evidence of an almost total absence of atmosphere. They do not prove, however, that there may not be one of great tenuity, of the order of 0.001 or 0.0001 of the density of the earth's atmosphere. The existence of such a thin atmosphere has not been established and it may be necessary to devise new methods of observation before this could be possible.

It has often been assumed that the moon at one time had an appreciable atmosphere and lost it because gravity at its surface was not strong enough to hold the atmospheric molecules. This assumption, however, is based on certain theories concerning the moon's origin which in themselves require proof.

The wholly wanting, or at least extremely tenuous, atmosphere precludes the existence of water in any quantity, for, if the latter existed, there would be an appreciable atmosphere of water vapor.

106. Changes on the Moon.—No changes of the prominent features of the moon's surface have ever been noted. There is a certain amount of evidence that a small crater named Linné was seen a century ago as a deep crater about 10 km (6 miles) in diameter. In 1866, Schmidt of Athens reported that he could not find it and since that time it appears as a shallow bright area, about the same size as the crater formerly drawn in that region. Certain considerations, however, do not permit unqualified acceptance of a real change, although the evidence as a whole is in favor of it. A number of similar cases have since been reported.

Within the last few years Prof. W. H. Pickering has reported seeing periodic changes taking place within many craters, paying particular attention to Eratosthenes. These consist in regular changes, occurring at each lunation, in color and outline of the different parts of the floor and inner walls of the crater. He interprets these to be in part small clouds of water vapor, deposits of frost or snow, and vegetation spreading over the surface and

undergoing its life-cycle within the lunar day. Observations by at least two other observers lend support to the occurrence of these changes, but in the interpretation of the things observed there is strong disagreement at the present time.

107. Effects of the Moon on the Earth.—There is a popular belief that the moon has a profound effect upon the weather; that the growth of crops depends upon the phase of the moon at the time of planting; etc. Extensive researches covering long periods have failed to find any real support for these widespread notions.

The moon, however, has one profound effect upon the earth in the formation of the tides, and in a slight degree it affects the magnetic field of the earth. The tides will be considered in Chap. VIII.

CHAPTER VII

PROBLEMS IN PRACTICAL ASTRONOMY

There is an almost endless variety of problems in practical astronomy, but, for the purposes of this course, only a limited number require consideration. These relate to the determination of time, latitude and longitude.

TIME

108. Sidereal Time.—In Sec. 17 it was stated that the rotation period of the earth has not varied an appreciable amount in the last 2000 years. The most important consideration for any time-keeper is that it maintain a constant rate, and so this property of the earth has been employed because no better time-keeper is known. The simplest unit of time is the time required by the earth to complete one rotation with respect to the stars. This unit is called the *sidereal day* and begins when the vernal equinox is on the meridian. It is divided into 24 sidereal hours, the sidereal hour into 60 sidereal minutes and the sidereal minute into 60 sidereal seconds.

The sidereal time at any instant is therefore the number of sidereal hours, minutes and seconds which have elapsed since the last meridian passage of the vernal equinox. Another way of saying the same thing is that the sidereal time at any instant is equivalent to the hour-angle of the vernal equinox.

109. Determination of Sidereal Time.—Sidereal time is determined by means of the transit instrument. It happens that there is no star exactly at the vernal equinox, and therefore its meridian passage cannot be observed directly. The right ascensions of the stars can be measured from the vernal equinox, however, because its position with respect to the stars is known, and if a star whose right ascension is 1^h is on the meridian we know that the vernal equinox crossed the meridian an hour ago, while if a star whose right ascension is 17^h is on the meridian then 17 sidereal hours have elapsed since sidereal noon. The sidereal time at any instant is therefore equal to the right ascension of any star on the meridian at that instant. This

leads to a third way of defining sidereal time, namely, the sidereal time is equal to the right ascension of the meridian for the instant under consideration.

Sidereal time is not satisfactory for everyday use, for, while the vernal equinox crosses the meridian about noon on the twenty-first of March, it crosses it about 4 minutes earlier each day, so that by the twenty-first of September it is sidereal noon at civil midnight. This brings us to a consideration of solar time.

110. Apparent Solar Time.—In general, we say that it is noon when the sun is on the meridian and that a solar day is the interval of time between two successive passages of the sun across the meridian. Time kept in this way is measured by the sun dial and is called *apparent solar time.* The apparent solar time at any instant is equal to the hour-angle of the sun. This kind of time, however, is not adapted to modern conditions, for the apparent solar days vary in length as measured by an accurate clock. Thus Jan. 1 is about 17 seconds longer than July 1 and the days in January average about 15 seconds longer than the days in July.

111. The Sun's Motion in the Ecliptic.—The variation in the length of apparent solar days is due to two causes: (1) The sun moves along the ecliptic and not along the celestial equator, and (2) the motion along the ecliptic is not uniform.

1. It is evident that, even if the sun moved uniformly along the ecliptic, about a degree a day, yet near the equinox a degree along the ecliptic EV would subtend a smaller angle at the celestial pole than a degree along the celestial equator QV (Fig. 68a.) On the other hand, near the solstices, where the ecliptic is about 23°.5 nearer the pole than the celestial equator, a degree along the ecliptic EC subtends a greater angle at the pole than a degree along the celestial equator QB (Fig. 68b). Hence, in the first case the eastward component of the sun's motion would be less than in the second case and therefore the apparent solar days would be shorter near the equinoxes than near the solstices.

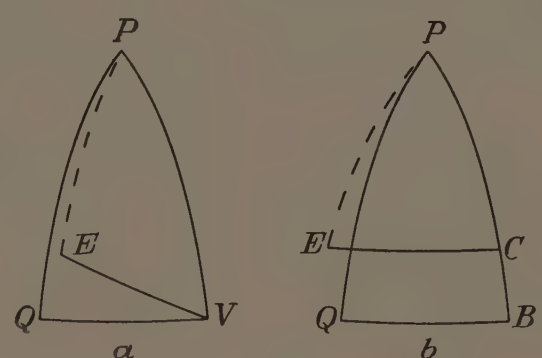


FIG. 68.

2. The earth moves in an ellipse and its motion, when near perihelion, is more rapid both in linear and angular velocity than when

near aphelion (see Sec. 130). As seen from the earth, the sun's motion along the ecliptic is therefore correspondingly more rapid at one time than at another. The more rapidly the sun moves eastward the longer the interval between two successive meridian transits, and *vice versa*.

112. Mean Solar Time.—In order to have days of uniform length, a day, called the *mean solar day*, has been devised, with hours numbered from 0 to 24. It is measured by a fictitious sun which moves uniformly along the celestial equator. It is mean solar noon when this fictitious sun is on the meridian and the mean solar time at any instant is the hour-angle of the fictitious sun. This sun completes its movement around the celestial equator in the same time as the real sun does around the ecliptic, so that the mean solar day is equal in length to the average apparent solar day.

113. The Equation of Time.—The difference in hour-angle between the real sun and the fictitious sun is known as the equation of time, and, according to the *American Ephemeris*, carries the positive sign when apparent solar time is greater than mean solar time. The values of the equation of time in Table II are for the year 1924. The values for these dates vary but little from year to year.

TABLE II

Jan. 1	-3^m	$12^s.4$
Feb. 12	−14	24.7
Apr. 15	0	0
May 14	+3	46.6
June 14	0	0
July 26	−6	19.8
Sept. 1	0	0
Nov. 3	+16	21.8
Dec. 25	0	0

114. Civil Time and Astronomical Time.—In general, it is not convenient to have the day begin at noon when the hour-angle of the sun is zero, and therefore in most countries the civil day begins at midnight. The astronomical day, however, has begun at noon, 12 hours later than the civil day, in order to avoid changing the date during the night when observations are in progress. This advantage has not been especially great, and, by international agreement, the astronomical day was made to agree with the civil day beginning Jan. 1, 1925.

115. Local and Standard Time.—From the definition of mean solar time it is evident that only places on the same meridian will have the same clock time, while places to the east will have later clock time and places to the west earlier clock time. The time measured by the mean sun for any particular place is called its *local mean time.* In order to avoid having different times at practically every station, the railroads of the United States introduced what is known as *standard time.* The country was divided into four districts and the time in each district was made 1 hour earlier than that of the district to the east and an hour later than the district to the west. These four times are known as Eastern, Central, Mountain and Pacific Standard Times and are the mean solar times of the 75th, 90th, 105th and 120th meridians west of Greenwich, respectively. These meridians, in general, are located near the centers of their respective districts, although the dividing lines are not straight but are arranged so that times are not changed except at division points of the railways.

Other countries have also adopted the same general plan so that now practically the entire civilized world is using it.

LATITUDE

116. The Circumpolar Method.—In Sec. 40 it was shown that the altitude of the pole is equal to the astronomical latitude of the observer. This simple relationship provides an easy method for the determination of latitude. The stars near the pole appear to describe circles around it, the polar distance of any star being the radius of its diurnal circle. In Fig. 69 let the circle be the diurnal circle of a star near the pole and the horizontal line the horizon under the pole. By means of a suitable instrument measure the altitude of the star when at a, its greatest distance above the horizon, and again 12 sidereal hours later when at b, its least distance above the horizon. The average of these two altitudes, each corrected for refraction, will be the altitude of the center of the circle, the pole P, and this altitude is equal to the astronomical latitude of the observer.

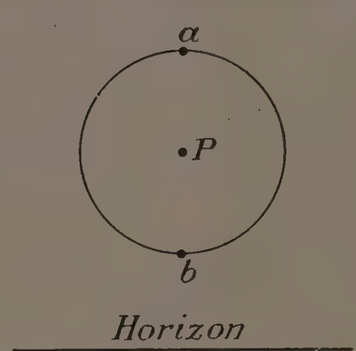


FIG. 69.—The circumpolar method of determining astronomical latitude.

117. A Second Method.—Let NS (Fig. 70) represent the plane of the horizon, P the pole, OQ the plane of the celestial equator,

Z the zenith of the observer at *O* and *a* and *b* two stars on the meridian. From the geometry of the figure it is evident that the arc *ZQ* is equal to the arc *PN*, that is, the declination of the zenith is equal to the altitude of the pole.

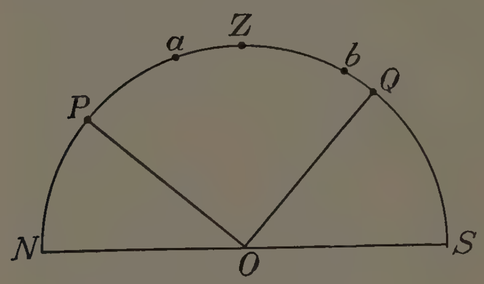


FIG. 70.—The method of determining astronomical latitude by the meridian altitude of a star of known declination.

Consider a star *b* whose declination *Qb* is known. By measuring its altitude above the south point *S*, and correcting this measured altitude for refraction, we have determined the arc *Sb*. After subtracting *bQ* the arc *QS* is obtained, and by subtracting this from 90° we have *ZQ*, which is equal to the latitude.

If the star is at *a*, between zenith and pole, then the measured altitude *Na*, added to the declination *aQ*, will give the arc *NPQ*. Subtracting $PQ = 90°$ from *NPQ* will give *NP*, the altitude of the pole.

LONGITUDE

118. Relation between Longitude and Time.—Since the earth rotates uniformly at the rate of 15° per sidereal hour, it is evident that two places differing by this amount in longitude will have a difference of exactly 1 hour in their sidereal times. The same relation between angle and time holds true for all places on the earth. Hence, if we know the difference between the sidereal times of two places, we also know their difference in longitude. The problem of determining the longitude of a place therefore resolves itself into the problem of determining its sidereal time and of obtaining in some way a knowledge of the same time of some place whose longitude is known. Two methods are in use to-day and these will now be considered.

119. Longitude by Transportation of Chronometers.—This method consists in carrying several carefully rated chronometers, set to the time of some particular meridian. The local time will be obtained by observations of sun or stars. The difference between the two times will give the difference in longitude.

More than one chronometer is used (1) in order to allow for accidents and (2) because no single chronometer can be trusted to maintain a constant rate. By averaging the time as shown by

several chronometers the probability of having nearly correct time is greatly increased.

120. Longitude by Time Signals.—If a place whose longitude is to be determined is in telegraphic or radio communication with some other place of known longitude, signals can be sent out by the clocks of the latter, and thus its time obtained with great accuracy. The local time of the place of unknown longitude must be determined as in the preceding method. The difference of time between the two places will correspond to the difference in longitude.

121. Longitude from Mean Time.—Thus far we have stated the situation on a comparison of sidereal times, but this is not essential. The earth also rotates uniformly with respect to the fictitious sun at the rate of 15° per hour of mean solar time, so that, if desired, the difference between the mean solar times can be used instead of the difference between the sidereal times.

Radio time signals are now becoming so common that it seems likely that in the near future this method of determining longitude both on sea and on land will be used almost exclusively.

122. Where the Day Begins.—Two places on opposite sides of the earth will differ by 12 hours in their time, and it is a practical question as to whether when it is one o'clock in the morning at Chicago it is one o'clock in the afternoon of the same day or of a different day in Calcutta. By general agreement the 180th meridian from Greenwich is taken as the place where the day begins. The calendar days are therefore different on the two sides of this line, the one to the west being a day later than the one to the east. In consequence, a ship crossing the line from east to west adds a day to its reckoning, while one going in the opposite direction will go back a day. Thus a ship going from San Francisco to the Philippines might approach the line on Tuesday. After crossing it, the day would be called Wednesday. Another ship crossing the line at the same time but in the opposite direction would reach it on Wednesday and then call the day Tuesday after it had crossed. For the second ship Wednesday would be repeated.

When Magellan's ships returned to Europe in 1522 after circumnavigating the globe it was found that they were one day behind in their reckoning. The ships had sailed westward in the same direction as the sun moves and in consequence the sun had risen and set once less for them than for the Europeans. Hence the loss of a day.

CHAPTER VIII

GRAVITATIONAL ASTRONOMY—THE CALENDAR

123. Newton's Law of Gravitation.—In 1687 Newton published his famous "Principia," in which he discussed the motions in the solar system on the basis of his law of gravitation. This law is now usually stated as follows:

Every particle of matter in the universe attracts[1] *every other particle with a force which varies directly as the product of the masses of the particles and inversely as the square of the distance between them.*

If m_1 and m_2 are the masses of two particles of matter and d the distance between their centers of mass, the force acting between the two may be expressed in the form of an equation as follows:

$$F = \frac{k \times m_1 \times m_2}{d^2},$$

where k is a constant whose value depends upon the units of force, mass and distance used.

124. The Attraction of Spheres.—It is not necessary to restrict our consideration of gravity to small particles of matter. Most of the heavenly bodies with which we have anything to do are approximately spherical, and Newton showed that a homogeneous sphere will act on a body outside it just as if its entire mass were concentrated in a point at its center. Two spheres of masses m_1 and m_2 will, therefore, attract each other as if their masses were concentrated at the centers a and b respectively (Fig. 71), and thus the distance between them will be the distance between their centers. This holds even if the spheres are in contact.

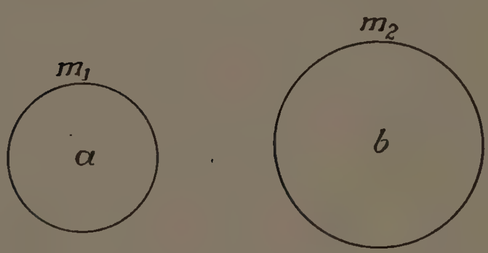


FIG. 71.—The attraction of spheres.

In considering a sphere's attraction for bodies on its surface it is necessary to remember that the *distance* through which the force of gravity acts is the radius of the sphere.

[1] We shall use the word "attract" as a matter of convenience without implying that gravitation is necessarily an attraction.

125. The Value of g.—At the surface of the earth a body falling freely under the action of the earth's gravitation will fall approximately 490 cm (16 feet) the first second, three times this distance during the next second, five times this amount the third second, etc., 980 cm (32 feet) being added each second. This value of 980 cm is known as the acceleration of gravity at the earth's surface and is usually designated by g. It is not a constant quantity, but varies slightly from place to place, depending upon the elevation above sea-level and the latitude. The latitude variation is caused by two factors: (1) the flattening of the earth toward the poles, which allows the observer to be nearer the center of the earth the farther he is from the equator; and (2) the centrifugal effect of the earth's rotation.

126. The Universality of Gravitation.—For some years before Newton's time it had been recognized that the planets moved about the sun, but no one had connected this motion with the earth's attraction for bodies at its surface. A genius like Newton was required to recognize the relationship.

While he was working on the general problem he realized that if his formulation of the law of gravitation were true then the earth's gravitation, which causes a free body to fall 490 cm toward the earth in 1 second, would also be operative in compelling the moon to move around the earth, the deviation of the moon's path from a straight line in 1 second being the amount by which it has been compelled to fall toward the earth. The proof of this follows.

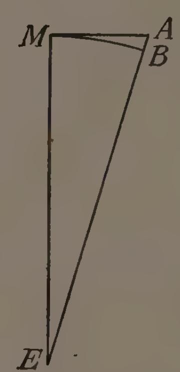


Fig. 72.—The earth's attraction for the moon.

In Fig. 72 let the earth be at E, the moon at M, MB the path of the moon described in 1 second and MA a straight line perpendicular to ME at M. The problem consists in determining AB, the amount by which the moon's motion deviates from a straight line in 1 second. In this case the moon's orbit may be considered a circle without serious error.

The moon's orbital velocity per second is equal to $2\pi \times 384{,}000$ km divided by the number of seconds in a sidereal month. This is approximately 1.023 km per second. The actual difference between the arc MB and the straight line MA is so small that MA can also be considered equal to 1.023 km.

In the right triangle EMA, EM is 384,000 km and MA is 1.023 km. It is therefore a simple matter to calculate the side EA.

This is found to be 384,000.0000014 km, approximately. Hence AB is equal to 0.0000014 km or 1.4 mm (0.05 inch).

The distance from earth to moon is approximately 60 radii of the earth. Hence the attraction of the earth at the moon's distance is $1/60^2$ that at the earth's surface. Therefore a body which falls 490 cm in 1 second at the earth's surface would fall one thirty-six-hundredth of that at the distance of the moon. This is 1.4 mm, thus agreeing with the amount the moon falls toward the earth in 1 second.

The extension of Newton's law to the motions of the planets was merely another step, and, with the exception of Mercury (Sec. 226), it explains all these motions.

Among the stars there are certain pairs which can be observed revolving around their common center of gravity, and, within the limits of error of the observations, the same law of gravitation is operative as that which causes an apple to fall to the ground. In view of these facts we feel reasonably safe in assuming that gravitation is universal.

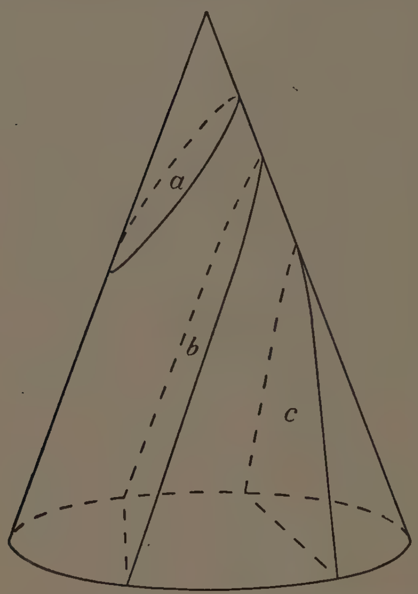


FIG. 73.—Sections of a right circular cone: *a*. Ellipse; *b*. Parabola; *c*. Hyperbola.

127. Conic Sections.—By analytical geometry it can be shown that if a right circular cone is cut by a plane, the intersection of the plane with the conical surface will result in three types of curves, depending upon the angle between the plane and the axis of the cone.

If the plane cuts across the entire cone (Fig. 73) the section is an *ellipse*, the particular shape depending upon the angle of the cone and the angle between plane and axis. If the plane is perpendicular to the axis the intersection is a circle which may be considered as a special case of the ellipse with both axes equal (Sec. 128).

When the plane intersects the cone and is parallel to one side of the cone, the intersection is a *parabola*. It is evident that the parabola is not a closed curve.

If the plane cuts the axis of the cone at an angle which is less than the angle between the axis and the plane of the parabola, the curve is called an *hyperbola*.

128. Properties of Conic Sections. *The Ellipse.*—The longest diameter of an ellipse is called the *major axis* and the shortest the *minor axis* (Fig. 74). These two axes cross at the center of the curve and are at right angles to each other. The half lengths of these two axes are usually called the semi-major and semi-minor axes and are designated by the letters a and b respectively.

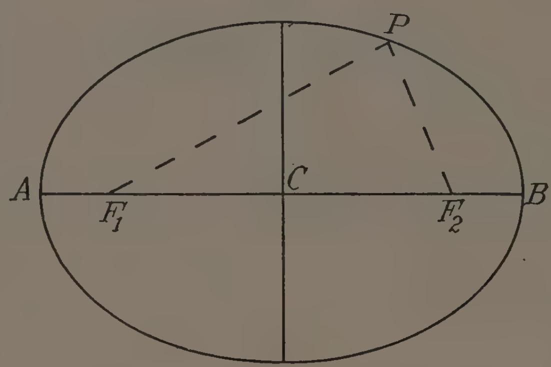


FIG. 74.—The ellipse.

On the major axis are two points F_1 and F_2 equally distant from the center. These two points are known as the *foci* of the ellipse. An important property of the curve is that for any point P, the sum of its distances from F_1 and F_2 is a constant and equal to $2a$, the length of the major axis.

It is evident that if the length of the major axis AB is kept constant while the foci are moved farther apart the resulting ellipse will be narrower than the one shown in Fig. 74, while if the foci are moved closer together the ellipse becomes broader. If the foci are moved to the center the ellipse becomes a circle and the major and minor axes are equal.

In order to define in a simple way the narrowness of an ellipse, the term *eccentricity* is employed. If we denote the distance from one focus to the center by c, the eccentricity e is defined by the equation

$$e = \frac{c}{a}.$$

When c is zero e becomes zero and the curve is a circle. As c increases e increases, the ellipse becoming narrower, and when $c = a$ the foci have moved to A and B and the ellipse becomes a straight line.

The Parabola.—If we take a straight line, such as CB in Fig. 75, at a point A draw the perpendicular AK and then select a point F on this perpendicular, we may draw a parabola. The property of this curve which we shall require is that any point P on the curve is equally distant from the line CB and the point F. The curve must therefore go through V, the midpoint of AF, and as we increase the distance from CB so we increase the distance from

F. CB is called the *directrix*, AF the *axis*, V the *vertex* and F the *focus* of the parabola.

Another property of the parabola is that if a tangent is drawn at any point D, and from this point DE is drawn parallel to the axis while DF is drawn to the focus, then the angles GDE and HDF are equal. This property of the parabola is employed in the construction of the mirror of the reflecting telescope and in the manufacture of the reflectors for searchlights and the headlights of automobiles.

The two sides of a parabola become more nearly parallel the farther they extend from the vertex, but they never become actually parallel.

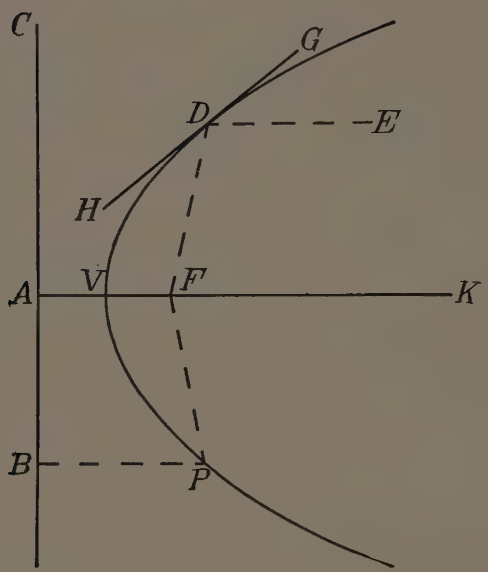


FIG. 75.—The parabola.

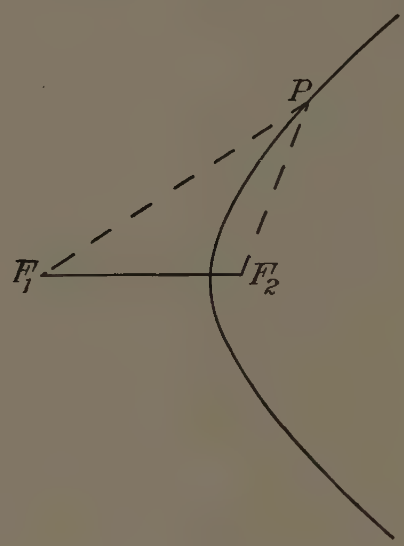


FIG. 76.—The hyperbola.

The Hyperbola.—The property of this curve, by means of which it may be drawn, is that for any point of the curve the difference between its distances from two fixed points is a constant. In Fig. 76 any point P is at such a distance from points F_1 and F_2 that $PF_1 - PF_2 =$ a constant.

The two sides of an hyperbola diverge more and more as the distance from F_2 increases, until, at great distances, they become practically two straight lines making a fixed angle with one another.

The points F_1 and F_2 are called the *foci* and the curve is symmetrical with respect to the line F_1F_2.

129. Gravitation and Conic Sections.—It can be shown mathematically that if a body is moving about a point under the action

of a force directed toward that point and varying inversely as the square of the distance from it, the path of the body must be a conic section, that is, its path will be an ellipse, parabola or hyperbola. Of the three possible paths the ellipse is the only closed one and therefore the only path in which one body may make repeated revolutions about another under the action of their mutual gravitation.

In the case of the orbits of the planets about the sun the point in the orbit nearest the sun is called *perihelion*, the point farthest removed *aphelion* and the line of the major axis is often called the *line of apsides.*

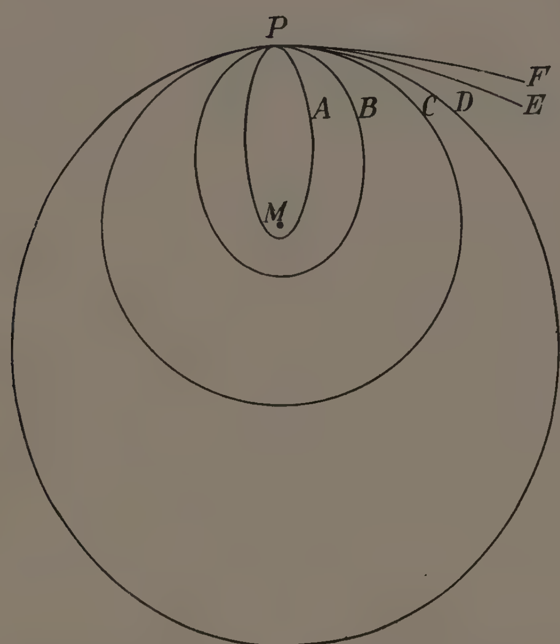


FIG. 77.—Curves described by a particle P about a mass M.

The question as to which curve will be followed by any particular body depends upon the velocity of the body and its direction of motion. As a simple illustration let us assume a small particle at the point P (Fig. 77), projected toward the right at various velocities and then moving solely under the gravitational attraction of a mass at M. If the initial velocity is small, the particle will move in the narrow ellipse A, and the point P will be the aphelion point. If the initial velocity is a little greater, it will move in ellipse B, which has less eccentricity than A. With a still greater initial velocity the orbit becomes a circle C. A greater velocity would compel the particle to move in the ellipse D with P as perihelion. Greater velocities still will cause the particle to move in the parabola E or the hyperbola F.

Should the velocity of projection be zero the particle would fall along a straight line toward M.

130. The Law of Areas.—If a particle moves about a given point the line joining the particle to the point is called the *radius vector*. If the particle is subject to no force except one directed through the point it can be shown that the areas swept over by the radius vector in equal times are equal. This holds true whatever the law according to which the force acts, provided only that it is directed through the given point. Thus, in Fig. 78, let P be the given point and the curve be the path of a particle moving about P under the action of a force through P. Then, if the radius vector sweeps over the area Pab while the particle moves from a to b in a certain time, it will later sweep over an area Pcd, which will be equal to area Pab, in an equal time interval. Since the radius vector Pa is less than the radius vector Pc, the arc ab will be greater than the arc cd. It therefore follows that the linear velocity of the particle will be greatest when at the point in its path nearest the point P.

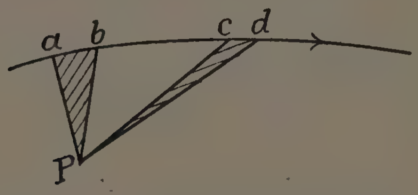


Fig. 78.—The general law of areas.

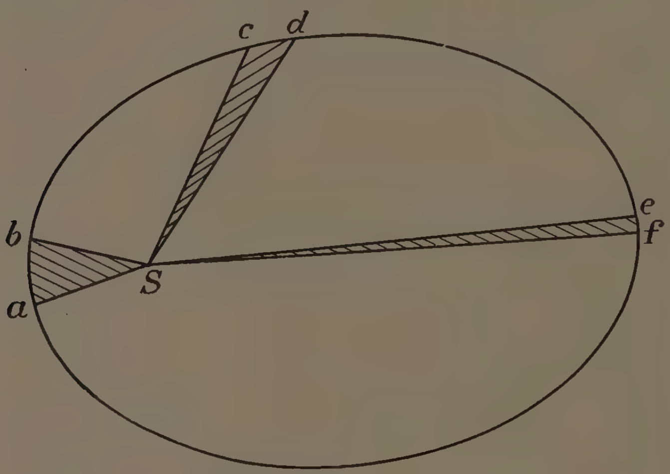


Fig. 79.—The law of areas for the ellipse.

The earth's orbit about the sun is an ellipse. If the sectors Sab, Scd and Sef in Fig. 79 are equal in area it is evident that the earth moves fastest along ab, more slowly along cd and slowest of all along ef. Accordingly, as seen from the earth, the sun will appear to move most rapidly along the ecliptic when the earth is moving most rapidly, and *vice versa*. This accounts, in part, for the varying length of apparent solar days (Sec. 111).

131. Perturbations.—If a body such as a planet is moving about the sun its orbit will be a smooth ellipse only in case there is no third body near them. The attraction of a third body will have an effect on both the others and these upon the third body. A simple illustration will show this.

In Fig. 80 let S be the sun, P_1P_2 the undisturbed orbit of an inner planet P and J an outer planet also moving about the sun. Only a portion of the outer orbit is shown.

J will attract both S and P. If P is at P_1 it will be affected more than S since it is nearer J. This difference of attraction will have the effect of pulling P forward in its orbit as well as outward toward J. If P is at P_2 then S will be attracted more than P. Hence the distance P_2S will be increased, or, so far as the effect concerns only the position of P with respect to S, we

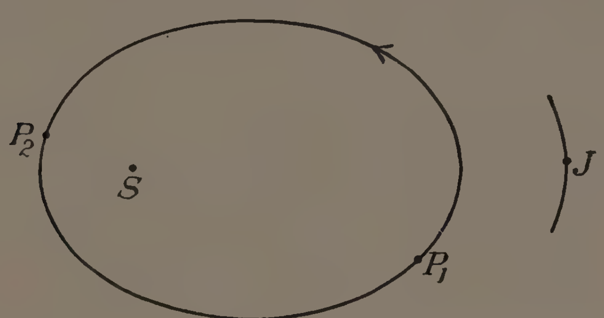


Fig. 80.

can say that near P_2 the planet P is forced away from S. It can also be shown that near P_2 there will be a force moving P ahead of its undisturbed place. Such effects of the presence of J are called *perturbations.*

The planet P will, in turn, cause perturbations of J, sometimes accelerating and sometimes retarding its motion, sometimes increasing and at other times decreasing its distance from S. These effects on J will in turn affect the motion of P.

Without considering further details it is evident that the subject of perturbations is very complex and it is not surprising that the problems arising when the mutual perturbations of several planets have to be taken into account are exceedingly long and difficult to solve.

132. Precession of the Equinoxes.—In Sec. 13 it was shown that the earth is not a sphere but a spheroid. The bulging of the earth at the equator is usually called the equatorial bulge. This bulge, with the cooperation of moon and sun, is the cause of

a slow movement of the plane of the equator which is called *precession*, and, since the positions of the equinoxes are determined by the plane of the equator, their motion is called the *precession of the equinoxes.*

Before considering the astronomical aspects of the problem it will be advisable to take up a brief study of the simple gyroscope (Fig. 81). If the wheel is rotating rapidly and the weight at the right just balances the wheel, the axis of the instrument will remain in a fixed position in space. If, however, we add an additional weight on the right, instead of the weight causing the heavier end to sink, the axis will maintain a fixed angle with respect to a horizontal plane but will slowly rotate about the vertical axis. This additional rotation involves a change in the direction of the axis of the wheel and in the plane of its rotation. This motion is called precession. The more rapidly the wheel rotates the slower will be the precession.

Fig. 81.—A simple gyroscope.

The additional weight introduces a force tending to throw the wheel up, but its combination with the angular momentum of the wheel produces a motion of the latter at right angles to the direction of the force.

Let us now return to a consideration of the earth and its equatorial bulge. For convenience we shall consider the bulge concentrated in a ring of matter around the equator (Fig. 82), since the spherical portion does not come into play except by its attachment to the equatorial bulge.

In the figure let M be the moon, points A and B the two portions of the equatorial bulge farthest from and nearest to the moon and C the center of the earth. Since M is nearer B than A it will exert a greater pull on the former. This will result in an

effort to pull B into the line CM. If the earth were not rotating this would be accomplished, but the great angular momentum of the rotating earth prevents B from moving toward CM, the plane of the moon's orbit, and, in combination with the additional force, the plane of the equator, while maintaining a practically constant angle with CM, gradually changes its position precisely like the plane of the gyroscope wheel.

When the moon is in the plane of the equator, as it is twice a month, this force vanishes, but the farther the moon is from the plane of the equator the greater the effect. The moon is therefore attempting to bring the plane of the earth's equator into coincidence with the plane of its orbit.

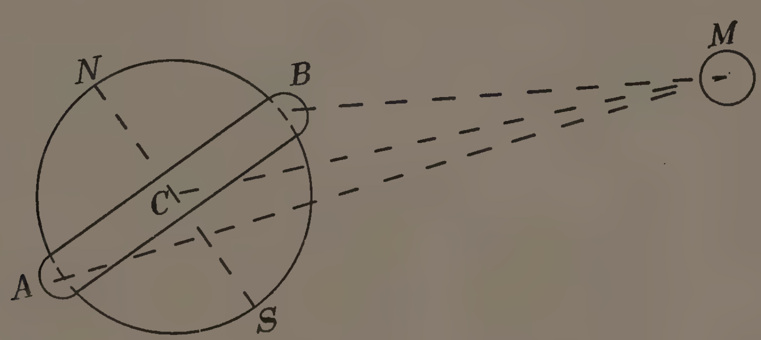


FIG. 82.—The physical cause of the precession of the equinoxes.

The sun, being in the plane of the ecliptic, in a similar manner attempts to bring the plane of the earth's equator into coincidence with the plane of the ecliptic. The effect of sun and moon on the rotating earth is to produce a slow change in the position of the earth's equatorial plane, although the angle between this plane and the plane of the ecliptic remains practically constant. This changes the intersections of the celestial equator with the ecliptic, that is, the equinoxes are slowly moving among the stars.

The direction of motion of the equinoxes is westward by an amount averaging $50''.2$ a year. In consequence of precession, the right ascensions, declinations and longitudes of the stars are slowly changing.

The moon's precessional effect is approximately two and one-half times that of the sun, because its proximity to the earth more than makes up for its almost insignificant mass as compared with the larger body. The planets also have a slight effect on precession, but this is practically negligible as compared with the combined effect of sun and moon.

133. Nutation.—Since the precessional forces of sun and moon vanish when these bodies are in the plane of the equator, it is evident that the rate of precession varies. In consequence, it is customary to break up the actual precession into two portions: a constant term, called the precession constant, amounting to $50''.2$ a year, and a variable term, which is called *nutation*.

134. Motion of the Celestial Pole.—The movement of the poles of the earth described in Sec. 14 has no effect on the position of the celestial poles, for that is a shifting of the body of the earth with reference to the axis of rotation. The direction of the axis with respect to the stars is unchanged so far as this effect is concerned. The precession of the equinoxes, however, since it involves a change in the celestial equator, produces a change in the position of the celestial poles among the stars. This motion is essentially in a circle around the poles of the ecliptic, the radius of the circle being about $23°.5$, the angle between the planes of the celestial equator and ecliptic. At the present rate of precession it will require about 25,800 years to complete one circuit of the celestial poles around the poles of the ecliptic.

Because of this motion of the poles various stars in turn become the pole star. About 4000 years ago the north celestial pole was less than 4° from the star α Draconis, while Polaris was then 25° from it. About 12,000 years hence the very bright star Vega will be only about 5° from the pole.

THE TIDES

135. The Tidal Forces.—In Fig. 83 let A, C and B be three points on a diameter of the earth and in line with the direction to

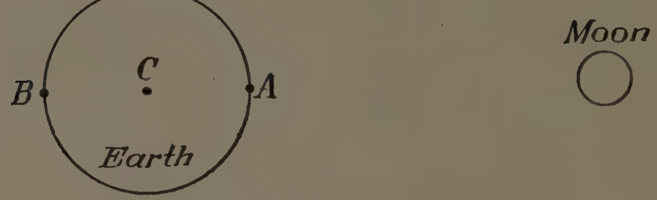


FIG. 83.—The cause of the tides.

the moon. Since A is nearer the moon than C it is evident that the moon will attract it more strongly than C, and C more strongly than B. The effect of this attraction will be to lengthen the diameter BA if the earth is not absolutely rigid.

If we consider the action of the moon with reference to the center of the earth C, then both B and A are, in effect, moved away from C just as if there were two forces directed toward A and B respectively from C. As seen from C, therefore, we can

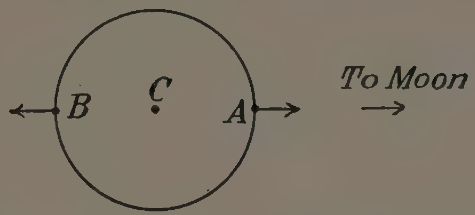


FIG. 84.—The tidal forces at two ends of a diameter of the earth when referred to the center.

indicate this effect by the arrows as in Fig. 84. The force at B is slightly less than that at A, since B is farther from the moon than A. When the forces with reference to C are analyzed for many points we get a result as indicated in Fig. 85.

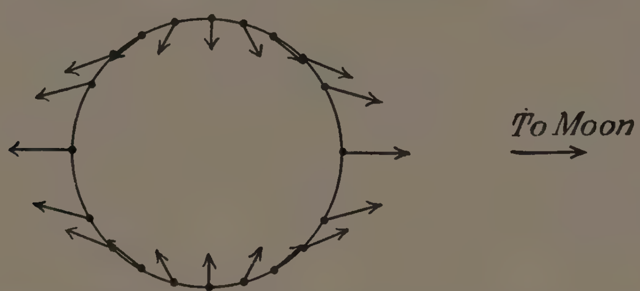


FIG. 85.—The tidal forces around a circumference referred to the center of the earth. (*Darwin.*)

136. Theoretical Tides.—If the earth were entirely covered by the ocean the effect of the tidal forces would be to move the waters of the ocean into two bulges, as indicated in Fig. 86, the bulge on the side toward the moon being a little greater than the one oppo-

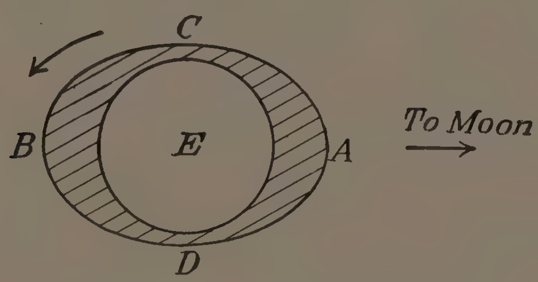


FIG. 86.—Theoretical tides.

site. The water would be deeper near A and B and shallower around the circle CED.

If the earth rotated on an axis perpendicular to the plane of the page and in the direction of the arrow, a point, which at

one time would be under A, would be under C, B, D and again under A in the course of one rotation. In this time the point in question would therefore have experienced two high and two low tides. Since the moon revolves around the earth in the same direction as the earth rotates on its axis the line joining B and A to the moon would have turned through the angle which the moon has moved. This amounts to approximately 13° a day. Hence the time when a point would be under A until it returned to the same position again would be $24^h\ 51^m$, the additional 51 minutes being the time required for the earth to turn through the 13°.

The earth rotates on its axis once a day, while the moon revolves about the earth once a month. It is therefore evident that unless the bulge or wave can travel westward as rapidly as the earth turns eastward the bulge will be dragged toward the east by an amount depending upon the freedom with which the tide can move.

137. Solar Tides.—The sun will cause tides precisely like the moon, except that since the tide-raising forces of the sun are less than those of the moon the solar tides are not as high as the lunar tides, being only four-ninths of the latter.

At new moon and full moon the solar and lunar tides are superimposed, while, when the moon is at first or third quarters, the crest of the one tide is in the trough of the other. When the two tides are combined the resulting tide is called *spring tide*, while when opposed it is called *neap tide*.

138. The Actual Tides.—The comparative shallowness of the oceans and the presence of the continents make the real tides very different from the simple theoretical situation. A tidal wave, once started, will move at a speed depending on the depth of the ocean and in a direction depending upon the direction and slope of the continental shores. The range of the tide from high to low at a port also depends upon the shape of the shore line and the shape of the bottom. The range along a comparatively straight coast is much less than at the head of a funnel-shaped bay.

RIGIDITY AND ELASTICITY OF THE EARTH

139. The Michelson-Gale Experiment.—In 1913, Professors Michelson and Gale of the University of Chicago carried out an experiment on the grounds of the Yerkes Observatory which gave considerable insight into the rigidity and elasticity of the earth as a whole. Two water-tight pipes, each about 500 feet long,

were buried in the ground about 8 feet below the surface. One was placed in an east-west and the other in a north-south position. These pipes were partially filled with water, their ends closed with plate glass and devices installed which allowed the water level at the ends to be determined with great accuracy.

The theory of the experiment is as follows:

If the earth yields like a perfect fluid to the tidal forces of sun and moon the surface of the water in the pipes will not change its apparent level. If, however, the earth has a certain amount of rigidity the crust will not yield completely and the water in the pipes will change its level by an amount equal to the difference between the actual yielding of the earth and the amount it would yield if it were a perfect fluid.

By computation it was possible to determine the amount the earth would yield if it were a perfect fluid, while observation of the change in the water level in the pipes showed the amount the earth did not yield. The difference between these two is the amount the earth actually yielded, and this was found to be about equal to the amount a homogeneous globe of steel would yield under the tidal forces involved. The rigidity of the earth was found to be the same in both directions.

Another result of the experiment was a determination of the rapidity with which the earth yielded to tidal stresses. The yielding was found to be essentially as if the earth had the elasticity of steel.

A more extensive series of observations made in 1916 and 1917, with improved facilities for measuring the changes of level, confirmed the earlier work.

The results of this experiment may be summarized as follows: *The earth has both the rigidity and the elasticity of a good grade of steel.*

THEORY OF RELATIVITY

140. The Einstein Theory.—A book on elementary astronomy is not the proper place in which to discuss the Theory of Relativity, as it belongs properly to theoretical physics, but so much has been said about it, both in popular and in technical publications, and the tests applied have been in the astronomical field, that a very brief statement appears desirable, especially concerning that portion of the theory which applies to gravitation.

The general theory of relativity in the form presented by Einstein in 1915 sets out with the intention of molding the laws of nature into such form that they shall be invariant under any transformation of coördinates. The Newtonian law does not satisfy this criterion. Einstein succeeded in finding a law which did satisfy it, however. The law was very different from the Newtonian law in the *way* in which it described planetary motion. In the Newtonian theory the thought at the back of the phenomena is one in which a mass—the planet—tends to go in a straight line with a constant velocity but is prevented from doing so and is controlled in its orbit by a force. It is this thought molded into quantitative form which the Newtonian equations express. In the general theory of relativity this thought is not dominant and the orbit becomes described in terms of a curve having certain fundamental mathematical properties. The actual orbits on the Newtonian theory and on the relativity theory are almost exactly the same. The great difference is in the language in which the orbit is described.

The characteristics of the orbit of Mercury, and in particular its large eccentricity, are such as to make that planet specially favorable for a realization of the small departure from the Newtonian orbit predicted by the Einstein theory, a departure which is associated with the motion of the perihelion of the orbit. The mere *existence* of a perihelion motion would not give much support to the Einstein theory as almost any departure from the Newtonian law would give such a motion. The crucial factor in the situation is the numerical agreement of the predicted perihelion motion with that actually observed (Sec. 226).

According to the views of Einstein his theory implies that the orbit of a light ray in passing by the sun should be the same as that which the same theory would give for the orbit of a planet which moved with the velocity of light and in this case, too, experiment confirms the theoretical prediction. This test will be explained in Section 202.

To an observer who falls freely in an elevator the apparent dynamical effects of gravity are concealed. If the observer allows a stone to leave his hand it will stay where it is relative to him, and will not fall to the floor of the elevator. Einstein postulates that the same acceleration which would serve to conceal the dynamical effect of gravity on the stone would also conceal whatever effect gravity might have on other phenomena such as chemical and optical phenomena. In this way the effects of gravity are regarded as the equivalent of those obtained by adopt-

ing as our frame of reference an accelerated system of axes. By an application of this idea Einstein was led to conclude that the effect of the sun's gravitational field on the vibrations of the solar atoms would be such as to increase the wave-length of each line as observed by us. This test was also successfully made as will be explained in Section 453.

141. Einstein Theory of Mass.—Another part of the Einstein theory concerns the notion of mass. Thus far we have assumed that the mass of a body is the same under all circumstances. The relativity theory, however, demands a variable mass, depending upon the velocity of the body. The formula is as follows:

$$M = \frac{m}{\sqrt{1 - v^2}},$$

where M is the variable mass, m the mass of the body at rest and v the velocity of the body in terms of the velocity of light.

For practically all bodies with which we have to deal the velocity is too small for us to detect this change of mass, but electrons emitted by radioactive substances or cathode rays in a vacuum tube have such high velocities that the question can be tested, and, within the limits of error of the observations, the results obtained satisfy the theory.

THE CALENDAR

142. Units of Time.—For different lengths of time different units are desirable. For short intervals the mean solar day is a convenient unit, but for longer intervals the synodic month and the year are not only convenient but natural. Unfortunately, these three units are not commensurable, but modern values of their lengths in terms of days make a comparison possible and not overly laborious.

The earliest calendars seem to have been predominantly lunar, and the Mohammedan calendar has remained so. Their year consists of 12 months and is reckoned as having sometimes 354 and sometimes 355 days. This kind of year does not keep step with the seasons, and gains on our year at the rate of about one in 34.

143. Three Kinds of Year.—Years are of different lengths, depending on the way in which they are reckoned. The *sidereal year* is the length of time required for the earth to make one revolution around the sun with respect to the stars. For 1925 its length is 365 $6^h\ 9^m\ 9^s.5$ and for the present is increasing at the rate of about $0^s.0001$ per year.

A second kind is the *anomalistic year*. This is defined as the time between two successive perihelion passages of the earth. It is at present $4^m\ 43^s.5$ longer than the sidereal year on account of the slow rotation of the line of apsides of the earth's orbit toward the east. Like the sidereal year, it is also increasing in length at the present time, but at a more rapid rate.

The third kind is the *tropical year* and is the one in common use. It is defined as the interval of time between successive passages of the sun through the vernal equinox. Because of the precession of the equinoxes toward the west this year is shorter than the sidereal year. For 1925 its length is $365^d\ 5^h\ 48^m\ 45^s.1$. Its value is slowly decreasing.

The tropical year is the one ordinarily used, as the seasons are thus kept in place in the calendar. If either of the other years were used the seasons would occur earlier and earlier until spring would begin in February, then in January, etc., for the northern hemisphere.

144. The Julian Calendar.—At the time of Julius Cæsar there was considerable confusion in the calendar and he determined to put it in order. He summoned the astronomer Sosigenes from Alexandria and with his aid a very simple system was devised. Each ordinary year was to have 365 and each fourth year 366 days. This new calendar was introduced in 45 B.C. and the beginning of the year, which up to that time had begun in March, was placed on Jan. 1.

145. The Gregorian Calendar.—The Julian calendar year had been taken as exactly 365¼ days in length, about $11^m\ 15^s$ too long. In the course of time the vernal equinox gradually approached the beginning of the month until toward the end of the sixteenth century it occurred on the eleventh of March instead of the twenty-first, as it did in the year 325 A.D., the year of the Council of Nice. To remedy this, Pope Gregory XIII issued an edict that the day following Oct. 4, 1582, should be called the fifteenth, thus bringing the vernal equinox back to Mar. 21, and that thereafter the years closing each century should not be counted as leap years unless divisible by 400. On this plan 1700, 1800 and 1900 were not leap years, but 2000 will be.

The plan was adopted generally by countries predominantly Roman Catholic, but Protestant and Greek Catholic countries were slow in following. England finally adopted it in 1752, Russia in 1918 and other Greek Catholic countries still more recently.

The length of the Gregorian calendar year is $365^d\ 5^h\ 49^m\ 12^s$.

This is still too long by 27^s and in the course of 3200 years the calendar will have to be corrected by one day.

146. A Modern Calendar.—Various plans have been suggested to simplify the system of weeks and months. One of the simplest is the following:

Divide the year into 13 months of 4 weeks each and add 1 day, which shall belong to no month but have a special name, such as New Year's Day. On leap years add an extra day, either following New Year's Day or preferably following some month in the summer, and give it some special name. Such a plan would allow the first, eighth, fifteenth and twenty-second days of each month to be any day decided upon, say Sunday, and a single sheet would answer for all months and years. All holidays would fall on the same day of the week in each year, and, if the ecclesiastical calendar were fixed so that Easter Sunday would fall on some particular Sunday, the entire calendar problem would be greatly simplified.

147. The Julian Day.—For some purposes the calendar involving the year, month and day is not very convenient, particularly when long intervals of time are concerned. Calendar confusion, omitted days and the like may cause errors. The simplest method would be to number the days consecutively. In time, large day numbers would occur, but the inconvenience would be more than counterbalanced by the increased accuracy.

In 1582, J. J. Scaliger suggested such a plan. He proposed that the beginning be made on Jan. 1, 4713 B.C., and the days numbered consecutively. His plan also involved years, but these are now seldom used. From a practical point of view, it would not have been necessary to begin so far back, as ancient dates cannot be fixed with any great degree of accuracy.

The system was adopted and is frequently used in certain classes of astronomical computations, where it has proved to be of value. The day used is called the *Julian day*.

The Julian day was made to agree with the astronomical day which began at noon, 12 hours later than the corresponding civil day. When the astronomical day was discontinued in 1925 it was also planned to change the Julian day so that it would begin at midnight. In order to avoid confusion, however, it was agreed, at the meeting of the International Astronomical Union in 1925, to continue the old plan of beginning the Julian day at noon.

January 1, 1926, was J. D. 2,424,517. From this other Julian day numbers can be calculated.

CHAPTER IX

THE SUN—OUR NEAREST STAR

148. Throughout the space in our vicinity are found many stars. Except on rare occasions we see them only in the night sky, because we are so near one of them that its brightness overpowers the others when our side of the earth is turned toward it. This nearest star, to which the earth is attached by the strong bonds of gravitation, is called the sun. From evidence to be presented later we shall see that the sun is a star of about average brightness, temperature, mass, density, chemical composition, etc.

The sun is in control of a planetary system. We have no evidence that any other star has a system of planets like our own, although such a situation is not improbable. While we are studying this dominant body in the solar system we must remember that the sun is a star and try to understand the stars as a whole from a study of the only one sufficiently near to permit detailed examination.

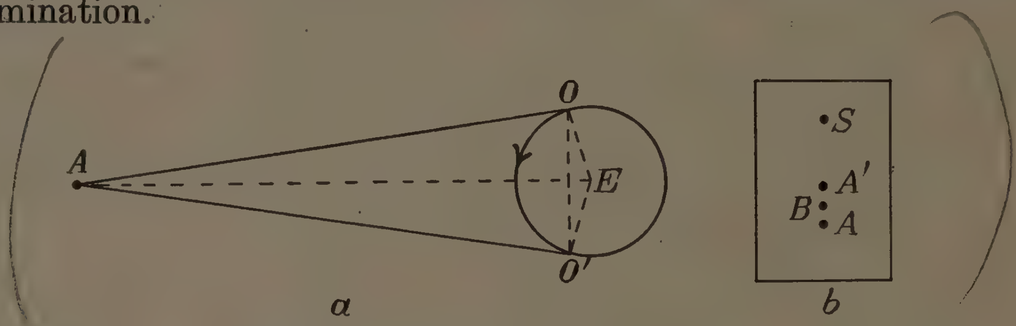


Fig. 87.—Asteroid method of determining the earth's distance from the sun.

149. Distance.—We have already considered one method of obtaining an approximate value for the distance of the earth from the sun in Sec. 25, where the aberration of light was studied. A second method, the observation of an asteroid (Sec. 248), is the most accurate method known at present. The principle involved will now be considered.

In Fig. 87*a* let the circle represent the earth whose center is at E, O and O' two positions of an observer at the equator who is carried around by the earth's rotation in the direction of the arrow, and

A an asteroid. Let us assume, for the sake of simplicity, that the asteroid and the earth are stationary in space and that the angles AOE and $AO'E$ are right angles.

From the elements of the asteroid's orbit, its position in the sky, as seen from E, can be computed with great accuracy. Let this position be B, in Fig. 87*b*, and let S be a star in the sky photographed on the same plate. When the observer is at O the line OA makes a small angle with EA, so that A would be seen lower than its computed position (A in Fig. 87*b*). Later, when the observer is at O', the asteroid would be elevated above its calculated position and would be photographed at A'. By measuring on the photographic plate the angular distances SA and SA', the value of AA' and hence the angle $O'AO$ is obtained. This is the amount by which the asteroid is displaced in the sky when the observer changes his position from O to O' because of the earth's rotation. Knowing the dimensions of the earth, the length OO' can be determined, the triangle AOO' solved and, finally, the distance AE determined. Knowing the value of AE in astronomical units from the elements of the orbits of the asteroid and the earth (Sec. 218), the value of the astronomical unit ~~in kilometer~~s is obtained.

The angle OAO' is small at best and it is therefore evident that the closer the asteroid the larger the angle, while the larger the angle the more accurately can it be measured. Hence Eros, the asteroid which comes nearest the earth, is especially important for the purpose of determining the sun's distance. The star-like appearance of the asteroid is also of great importance, as its small image on the photographic plate permits very accurate measures of the distances SA and SA'.

The ideal conditions assumed are not realized. The asteroid and the earth are both moving in their orbits about the sun; with one exception observatories are not located at the equator and the asteroid cannot be observed on the horizon, so that the angles AOE and $AO'E$ are not right angles. These conditions introduce additional work in the computations but the principle outlined is the same.

The determination of the sun's distance is affected not only by any errors which may be inherent in the accurate measurement of the angle OAO' but also by any errors in the determination of the earth's equatorial radius. Since this is the only measured length involved, it is evident that the highest degree of accuracy in its determination is desirable.

150. Parallax.—In Fig. 88 let AE represent the equatorial radius of the earth and SE the mean distance from earth to sun. The angle at S, subtended by AE, is termed the sun's *equatorial parallax*. The present adopted value for this angle is $8''.80$, which corresponds to a distance SE of 149,504,200 km (92,897,400 miles). This value is probably correct to within about 100,000 km.

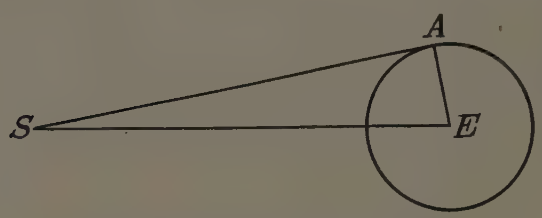


Fig. 88.—Solar parallax.

151. Dimensions.—The present adopted angular diameter of the sun at mean distance is $31'\ 59''.26$. This corresponds to a diameter of 1,391,100 km (864,390 miles). If the sun were a hollow sphere and the earth placed at its center, the moon, at its present distance from the earth, would be only a little over half way from the center to the surface of the sphere.

The immense size of the sun as compared with the earth may more easily be realized by a comparison of their volumes. Since the volumes of spheres are proportional to the cubes of their diameters, we may write

$$\text{volume of sun} : \text{volume of earth} :: 1{,}391{,}100^3 : 12{,}740^3.$$

Solving this proportion, we find the volume of the sun is approximately 1,300,000 times the volume of the earth.

152. Mass, Density, Etc.—The sun's mass is approximately 333,000 times the mass of the earth. Since its volume is 1,300,000 times that of the earth, its mean density is one-fourth of the earth's, or about 1.4 on the water standard.

The force of gravity at the sun's surface is nearly 28 times that at the earth's surface. A man weighing 175 pounds here would weigh nearly 2.5 tons there.

153. Sun-spots.—These were discovered as soon as the newly invented telescope was turned on the sun early in the seventeenth century. The general appearance of a spot is that of a dark center, called the *umbra*, usually surrounded by a less dark border, the *penumbra*. The shape of spots varies and even the shape of an individual spot undergoes changes, but the tendency is toward roundness.

154. Size of Spots.—The size of spots varies within wide limits, the smallest which can be detected being about 500 km (300 miles) in diameter, while an occasional large one approaches 100,000 km (60,000 miles).

Spots usually occur in groups (Fig. 89) and the length of the penumbra surrounding a group may be over 200,000 km (125,000 miles).

155. Development and Duration.—The beginning of a sun-spot is hard to determine, but usually a disturbance of some sort is noted, followed by a minute black area which enlarges rapidly to be the umbra of the fully developed spot (Fig. 90). The penumbra is not seen until the umbra is well marked.

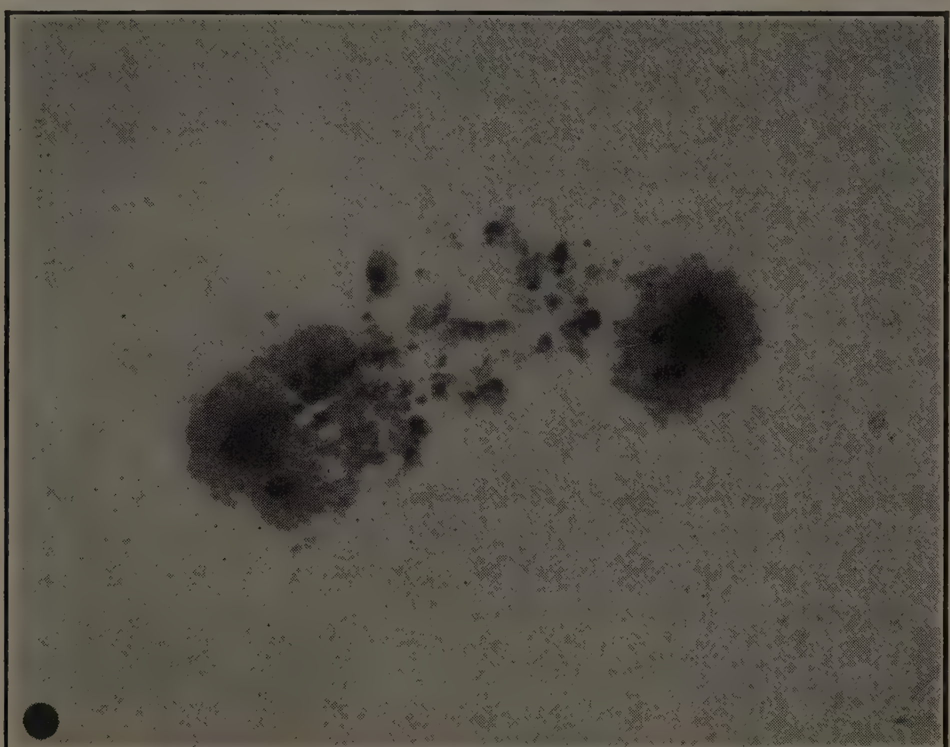


FIG. 89.—Great sun-spot group of Feb. 8, 1917. Small black circle represents the earth on the same scale. (*Photographed at the Mt. Wilson Observatory.*)

The breaking up of a spot occurs when one or more extensions of the penumbra shoot inward over the umbra and divide it. If such a division into two or more parts endures for a time the parts move away from each other. The final dissolution comes when the penumbra rapidly encroaches on and ultimately obliterates the umbra.

The life of a spot may be as short as a few hours, but there is a record of one which lasted 18 months. The average duration may be placed at from 1 to 2 months.

156. Periodicity of Sun-spots.—About 1843, Schwabe of Dessau called attention to the periodicity of spots and showed that, on the average, the times of maximum number of spots

occur about every 11 years. From the time of maximum the number gradually diminishes until, at times, weeks may pass without a spot being seen. After such a minimum the number of spots gradually increases until another maximum develops.

157. Wolf's Sun-spot Numbers.—Some years ago Wolf of Zurich collected all available observations of spots and arranged them in accordance with an empirical formula, $N = k(10g + f)$,

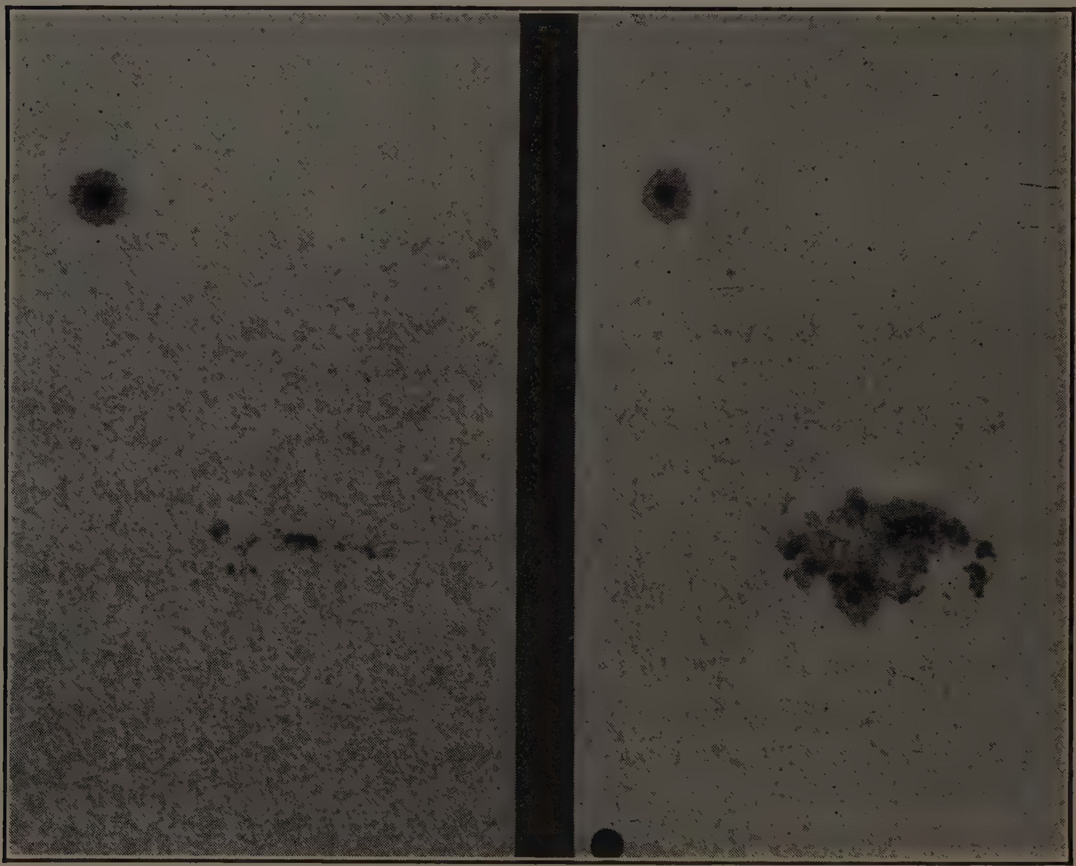


FIG. 90.—Twenty-four-hour development of a sun-spot, Aug. 18 and 19, 1917. (*Photographed at the Mt. Wilson Observatory.*)

where N is the Wolf number, k a constant depending upon observer and instrument, g the number of spot groups and f the total number of spots both isolated and in groups. These numbers were then plotted as shown in Fig. 91. The work is being continued by his successor, Wolfer, who supplies the results from time to time. The sun-spot curve in Fig. 91 was drawn from revised values of the annual means as given by Wolfer.

From the figure it is evident that the maxima are not of equal height, that the rise, in general, is more rapid than the fall and that the time between maxima or minima is not the same. The

average time between maxima is about 11.2 years, although some recent determinations give about 11.5 years. The last maximum occurred in August, 1917, according to Nicholson of the Mt. Wilson Observatory.

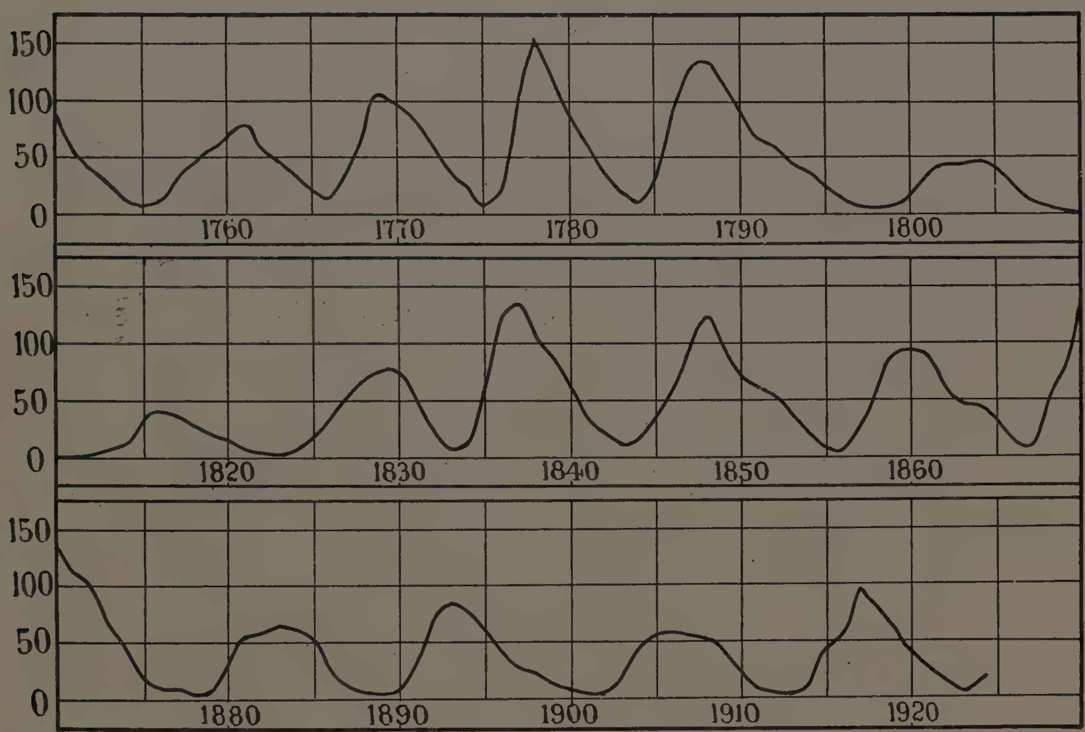


FIG. 91.—The sun-spot curve, according to Wolf's sun-spot numbers. (*From data by Wolfer.*)

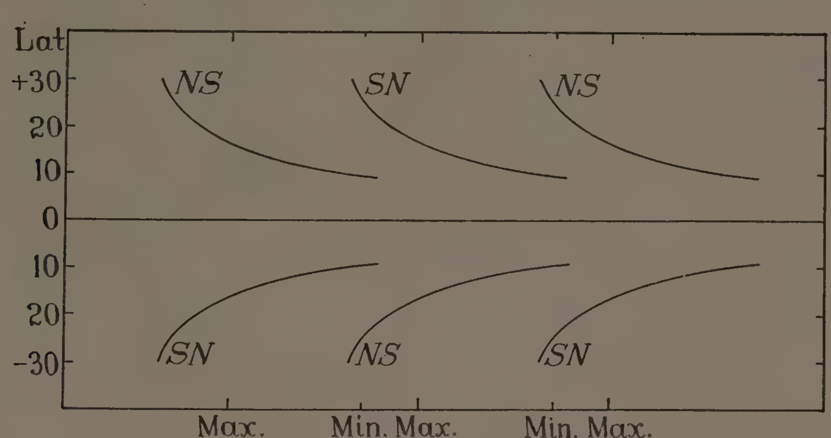


FIG. 92.—The mean latitude of sun-spots in successive cycles. The letters *N* and *S* show the prevailing magnetic polarity in bipolar spots.

158. Distribution of Sun-spots.—Sun-spots are seldom found beyond latitudes ±40°. They usually occur in about equal numbers on either side of the solar equator, when means covering several years are taken, although from 1672 to 1704 none were observed in the northern hemisphere. This, however, was a marked exception to the rule.

The main spot belts occur between 10° and 30° on either side of the equator. The beginning of a new spot cycle shows itself by two regions of spots at about latitude 30° north and south. The belts of disturbance gradually approach the equator and die out near latitude 10°. Spot maximum occurs when the spot regions are approximately in latitude 16°. Before the disturbances have

Fig. 93.—Vortex motion in sun-spots. Note that whirls in opposite direction are indicated for the two spots. (*Photographed at the Mt. Wilson Observatory.*)

died out entirely, new ones are beginning again at 30°. Figure 92 shows this diagrammatically. The letters in the figure will be dealt with in Sec. 162.

159. Temperature in Sun-spots.—There is good evidence that the spot umbra is considerably cooler than adjacent bright portions of the sun. The lower temperature is largely responsible for the relative darkness of the umbra.

160. Sun-spot Spectra.—The spectrum of the umbra of a sun-spot differs in some respects from the ordinary solar spectrum in that some of the lines are stronger and some weaker than the normal lines. In 1896, Zeeman of Amsterdam found that when a source of light is placed between the poles of a powerful magnet the lines in the spectrum are split into several components and that the light in these components is polarized in different ways. In 1908, Hale found the behavior of the lines in the spot spectrum like the behavior of the same lines in a magnetic field, and thus made the important discovery that a sun-spot has the properties of a magnet.

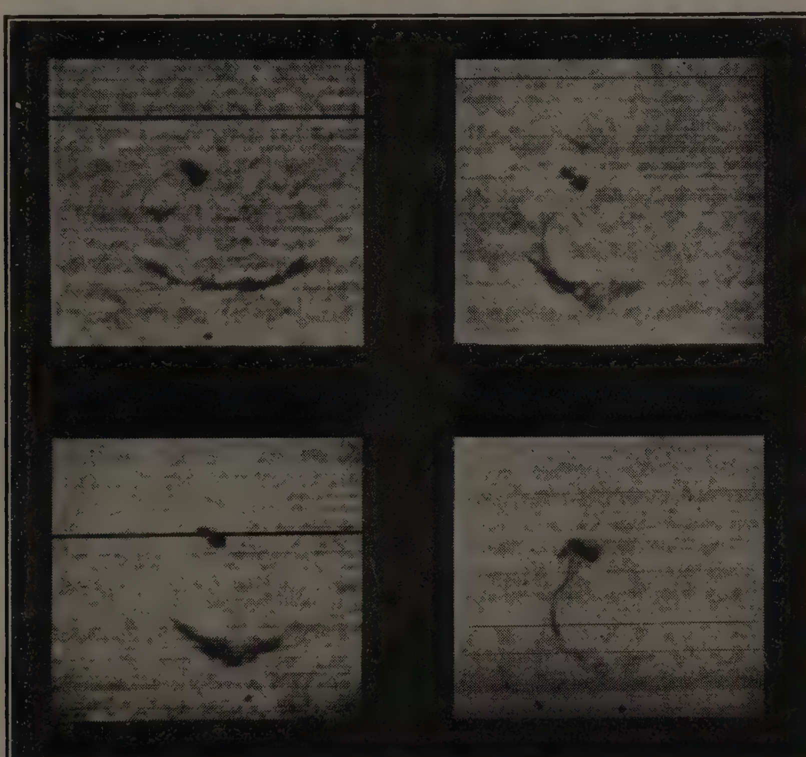


Fig. 94.—Motion of hydrogen flocculus toward a sun-spot.
1. June 2, 1908, 6:10 a.m. 3. June 3, 5:13 p.m.
2. June 3, 4:58 p.m. 4. June 3, 5:22 p.m.
Scale 1 cm = 80,000 km; 1 inch = 125,000 miles. (*Photographed at the Mt. Wilson Observatory.*)

161. Nature of Sun-spots.—The nature of sun-spots has been the subject of much speculation ever since their discovery, but it remained for Hale of the Mt. Wilson Observatory, in 1908, to show that spots, in general, are vortices with a downward suction. The vortex motion is shown in the alignment of the material around the two umbræ in Fig. 93, and suction is clearly indicated in Fig. 94.

The usual explanation of the magnetic character of sun-spots has been as follows:

Many years ago Rowland showed that a charge of electricity in motion is the equivalent of an electric current and more recent work has shown that a current is, in reality, a stream of electrons. At the high temperatures prevailing on the sun there must be many free electrons. When these are caught in the vortex the

Fig. 95.—The great tower-telescope of the Mt. Wilson Observatory especially designed for solar investigation. Total height 52 meters (170 feet).

effect is similar to an electric current flowing around the coils of a helix, which, as is well known, develops a magnetic field and has the general properties of a magnet. This offers a simple explanation of the magnetic properties of sun-spots, but recent investigations show that it is no longer adequate and some other must be found.

The depth to which the spot vortex descends is not known. St. John has shown that at elevations exceeding 1500 km (900

miles) above the apparent surface of the sun the gases are flowing into the spot, while below that level they are flowing out. The vortex, in all probability, descends below the level of the apparent surface, but it has not yet been possible to learn what takes place there.

162. The Law of Sun-spot Polarity.—According to their magnetic properties, spots may be classified as unipolar, bipolar and complex. *Unipolar* groups are either single spots or groups of spots exhibiting the same magnetic polarity, like one end of a bar magnet. *Bipolar* groups, in their simplest form, are composed of two spots quite close together and showing opposite magnetic polarity. *Complex groups* are those in which the polarities are irregularly distributed.

Bipolar groups are most common, 61 per cent of all groups classified at the Mt. Wilson Observatory since 1908 being of this character. In general, the line joining the two spots is approximately parallel to the solar equator. On account of the sun's rotation, one spot leads the other as they pass across the disc of the sun. The first is called the *preceding* and the other the *following* spot.

In 1925, Hale and Nicholson announced the following important discovery:

> "The sun-spots of a new 11.5-year cycle, which appear in high latitudes after a minimum of solar activity, are of opposite magnetic polarity in the northern and southern hemispheres. As the cycle progresses the mean latitude of the spots in each hemisphere steadily decreases, but their polarity remains unchanged. The high-latitude spots of the next 11.5-year cycle, which begin to develop more than a year before the last low-latitude spots of the preceding cycle have ceased to appear, are of opposite magnetic polarity."

This law of reversal of polarity in successive cycles was found to hold in all but 41 cases out of a total of 1735 bipolar groups. It is therefore evident that the full spot period, at least that referring to magnetic polarity, is 23 years, and not 11.5 years as it is for spot frequency. Turner of Oxford has also shown that there is a difference between successive periods of spot frequency which points to the double period as well. We may therefore ultimately find that the true spot period, as to both magnetic polarity and frequency, has a mean duration of 23 years.

The law of spot polarity is indicated in Fig. 92. The pairs of letters, *N* and *S*, refer to the two spots of a bipolar group, the letter at the right indicating the preceding spot of the pair. North-seeking poles are indicated by *N* and south-seeking poles by *S*.

163. Magnetic Storms and Auroræ.—Occasionally, the earth experiences a magnetic storm. This means that the compass needle is not steady but moves about in irregular fashion over a small arc and that fluctuating currents occur in telegraph and telephone lines which may be so strong that communication is interrupted. Whenever these occur there is found to be a disturbed area, usually accompanied by large spots, on the sun.

At the time of a magnetic storm unusually brilliant displays of the aurora may be seen if the disturbance occurs during the night and the sky is clear.

The explanation of these two phenomena now generally accepted is as follows:

In the solar atmosphere there are many free electrons. Whenever there is a disturbance of the solar surface there is an especially strong outflow of these electrons somewhat in the form of a beam. If the beam strikes the earth's atmosphere the gases at great heights become ionized, and therefore luminous.[1] The beam is also like an electric current which is accompanied by its magnetic field. The result is a disturbance of the earth's magnetic field, which is shown by the wavering of the compass needle, and strong electric currents are induced in telegraph and telephone wires.

164. The Sun-spot Curve and Related Phenomena.—Many phenomena, such as sun-spots, the variations of the earth's magnetic field, the variation in the solar constant, the number and intensity of terrestrial auroræ, the shape of the solar corona, the faculæ and the solar prominences, have periods which run parallel to each other and therefore are probably more or less closely related. The underlying cause is within the sun, but thus far no adequate explanation has been forthcoming to account for the solar changes which manifest themselves in spots, etc., and in turn influence the earth.

[1] The spectrum of the aurora consists of bright bands and lines. These are due to nitrogen and to oxygen in the presence of helium, according to McLennan and Shrum.

In addition to these, many other variable phenomena, ranging from the flight of insects to the price of wheat, have been thought to show a periodicity which is analogous to the sun-spot curve. How much reliance should be placed in these ideas it is difficult to say, but for the present it seems best not to consider them too seriously.

165. Sun's Rotation.—The sun rotates on an axis from west to east, just like the earth. The plane of the sun's equator makes an angle of 7° 11′ with the plane of the ecliptic. The earth is at the intersection of the two planes about June 6 and Dec. 8. The north pole of the sun is turned toward the earth 7° about Sept. 8 and the south pole similarly about Mar. 7.

There are several ways of determining the sun's period of rotation, but we shall consider only two, the spot method and the application of Doppler's principle.

Fig. 96.—Sections of photographs of the sun taken Aug. 1 to 5, 7 and 11, 1893, showing development of sun-spots and motion across the sun's disc. *(Photographed by Wilson at the Goodsell Observatory.)*

166. Rotation by Spot Method.—Sun-spots are seen to move across the sun's disc (Fig. 96), disappear from view at the western edge, and, if of sufficient duration, reappear later at the opposite

edge and again cross the disc. Observations of this character show that the average time between two successive transits across the sun's central meridian is about 26.8 days. This period is called the sun's *synodic rotation period.*

The synodic period is not the actual rotation period, for the earth has moved ahead nearly 30° in its orbit in the interval, so that the apparent central meridian is not the same. After allowing for the effect of the earth's motion, the sun's period of rotation, called its *sidereal period,* is found to be approximately 25.0 days.

167. Rotation by Doppler's Principle.—The western edge of the sun is moving away from the earth and the eastern edge is approaching. If images of these two edges are brought to the slit of a spectrograph the lines in the spectra of the two edges will be shifted relatively to each other. By measuring the amount of the shift the velocities of the two edges relative to each other can be determined. Knowing this velocity and the distance around the sun, the rotation period follows.

168. Law of Solar Rotation.—Observations of sun-spots have shown the remarkable fact that the rotation period depends upon the solar latitude of the spots used. Many series of observations have been made to study this phenomenon, but we shall give only the more recent values obtained by E. W. and A. S. D. Maunder from the Greenwich photographic observations of 1879 to 1901. These results, depending on 1871 spot groups which lasted 6 days or more, may be summarized as follows:

Table III

Spot latitude, degrees	Period, days	Spot latitude, degrees	Period, days
0	24.6	20	25.2
5	24.7	25	25.6
10	24.8	30	25.8
15	25.0	35	26.6

Few spots are found beyond 40° latitude, either north or south, so that the spot method is not available for higher latitudes. To study rotation there Doppler's principle must be called upon. One series of observations of this character, made by Plaskett and De Lury, gave the following results:

TABLE IV

Latitude, degrees	Period, days	Latitude, degrees	Period, days
0	25.3	35	28.0
5	25.4	40	28.7
10	25.6	50	30.4
15	25.8	60	32.2
20	26.2	70	33.8
25	26.7	80	35.0
30	27.3	90	35.4

The two methods agree moderately well in results. Each shows the shortest period at and near the equator, the period increasing with the latitude. No satisfactory reason has been found to explain this peculiar law of solar rotation. There is some evidence also that there is a variation in the period, depending upon the level in the solar atmosphere of the element whose lines are used, in the sense that the higher the level the more rapid the rotation. From slight differences in values obtained at various times there is also a possibility that the rotation is not absolutely constant at any one latitude and level.

169. Temperature.—The actual temperature of the sun is not definitely known but its effective temperature[1] at the apparent surface is about 6000° absolute.[2] The temperature undoubtedly increases rapidly as the center is approached and it appears probable that at the center the temperature can be expressed only in millions of degrees.

170. Solar Constant.—Much work has been done to determine the amount of energy the sun sends to the earth. The latest results of Abbot of the Smithsonian Institution of Washington show that the amount of energy received per square centimeter of surface perpendicular to the sun's rays (after eliminating the absorption in the earth's atmosphere) is equal to 1.94 calories[3] per

[1] The effective temperature is defined in physics as the temperature of a so-called "black body" which will radiate an equal amount of heat per unit of area.

[2] The absolute temperature is usually used in the discussion of stellar temperatures. Zero degrees absolute corresponds to −273°C. To reduce absolute values to the Centigrade scale subtract 273°.

[3] A calorie is the amount of heat required to raise the temperature of one gram of water one degree Centigrade.

minute, on the average. This quantity is known as the *solar constant.*

The solar constant is not strictly a constant quantity. It has been found to vary slightly from day to day and it may be either above or below the average value for months at a time. These variations amount to as much as 5 per cent either way from the mean. In general, there is also a relation between solar activity, as indicated by the number of spots visible, and the solar constant. Abbot has shown that for the period 1918 to 1924 the greater the number of spots the greater the solar constant.

171. Amount of Energy Radiated by the Sun.—If the radiation from the sun at the earth's distance amounts to 1.94 calories per square centimeter per minute, it is evident that the total radiation must equal 1.94 times the number of square centimeters in the surface of a sphere of radius 150,000,000 km calories per minute. This enormous amount of energy would melt a layer of ice about 11 meters thick over the entire surface of the sun in 1 minute. This means that each square meter of the sun's surface is radiating energy at the rate of 80,000 horsepower continuously.

172. Light of the Sun.—Various determinations of the amount of light received from the sun as compared with that received from the full moon have been made. Russell has recently discussed these and finds that the light of the sun is equivalent to about 465,000 times the light from the full moon. If the entire sky above the horizon were packed with full moons edge to edge they would give only about one-sixth as much light as the sun.

173. Source of Sun's Heat.—The sun is not merely a hot body cooling off nor is it a body which is burning, for at the high temperature which obtains there no chemical combinations are possible except possibly in sun-spots. If the sun's mass were composed of pure carbon and this were completely burned in oxygen, it would radiate heat at the present rate for less than 8000 years. As we shall see later, this short time is almost negligible in the life of the sun.

Various theories to account for the maintenance of the solar radiation have been proposed, but the only one which seems worthy of consideration at the present time is the one which places the source in the disintegration of the atoms of the sun's mass. Much still remains to be done before this theory can be considered as proved, but it appears to be the only one which will

account for the radiation of the sun for the period of time which now seems necessary.

Recent studies of the atom show that there is an enormous amount of energy locked up in each atom. Under certain conditions not yet clearly understood atoms disintegrate and give up their store of energy. It would require the disintegration of but a small amount of the sun's mass to maintain the present rate of radiation for millions of years.

174. Constancy of Sun's Radiation.—As stated in Sec. 170, the measurements of the solar constant indicate fluctuations from day to day and even changes in value which endure for months, but, from the evidence available, the average radiation of the sun from year to year is remarkably constant. The fruits grown to-day in Italy are known to be like those grown 2000 years ago. Some of the giant sequoias of California are at least 3000 years old. These trees require reasonably moderate temperatures and precipitation. We therefore conclude that, in general, there has been no marked change of climate in southern Europe and in California for some thousands of years. Since the earth's temperature and climate are almost wholly dependent upon solar radiation, we conclude that no marked change in radiation has occurred in that interval.

Geological evidence carries the earth's history backward for an almost indefinite period. Fossil remains of plants and animals indicate that there has been no extraordinary change of climate affecting the entire earth for a period reckoned in millions of years. We are therefore justified in concluding that for some millions of years at least the sun has been radiating energy at about its present rate.

175. The Photosphere.—The apparent surface of the sun is called the *photosphere.* It was formerly believed that this surface was formed by a layer of clouds composed of small liquefied particles of the less easily volatilized elements composing the sun. This view can no longer be held, for at the high temperature known to exist at the photosphere all known elements would be in the gaseous state. Since the internal temperature is very much higher than that at the surface, it is necessary to assume that the sun is wholly gaseous, the density increasing with the depth below the outer boundary.

No gas is wholly transparent. Accordingly, our ability to see into (receive light from) the gaseous sun is determined by the

density of the gases composing its outer layers. For a depth approximating 15,000 km (10,000 miles) these gases are fairly transparent, but below this level the density is sufficient to produce marked absorption. Hence light originating below a depth of about 15,000 km does not reach the eye, while that coming from slightly lesser depths will be partially absorbed and scattered by overlying layers and a portion will reach the observer. From the evidence available most of the light emitted by the sun comes from a thin layer lying immediately above the level of total absorption. No definite value of the thickness of this layer can be given, but it seems to be of the order of only a few hundred kilometers. At the earth's distance from the sun this layer is hardly of appreciable thickness, and therefore acts essentially like a luminous surface. This apparent luminous surface is the photosphere.

The intensely heated gases of the photosphere produce light of all wave-lengths, hence its spectrum is continuous. The mean pressure within the layer is probably less than 1 atmosphere (1033 grams per square centimeter, or 15 pounds per square inch).

176. Appearance of Photosphere.—The photosphere is not a surface of uniform brightness but has a mottled appearance (Figs. 89 and 90) to which the older observers gave the name of "rice-grain structure." The "grains" are from 300 to 800 km in diameter, about the smallest area which can be distinguished easily on the solar surface. The probable explanation of the mottled appearance is that there are ascending and descending currents of gases at the photospheric level, the ascending ones bringing up hotter material from lower levels and the descending ones carrying down cooler and therefore darker matter.

Occasional sun-spots will also be seen. These look like black areas in the photosphere. Around the spots bright areas, called *faculæ*, usually make their appearance.

The general brightness of the photosphere is greatest at the center of the sun's disc and decreases rapidly near the edge. This is especially well seen on photographs (Fig. 97). It is easily explained as an absorption effect, since the light from the limb must take a much longer path through the sun's atmosphere[1] than that coming from the center of the disc.

[1] The term *atmosphere* as applied to the sun means that portion lying above the level of the photosphere.

177. The Reversing Layer.—The gases of the solar atmosphere lying immediately above the photosphere are of extraordinary interest. The pressure within this layer varies from about 0.1 atmosphere at the bottom to 0.0001 at the top, according to St. John and Babcock.[1] The average temperature is lower than that of the photosphere but still high enough to radiate well. We therefore have the condition of a "luminous gas under low pres-

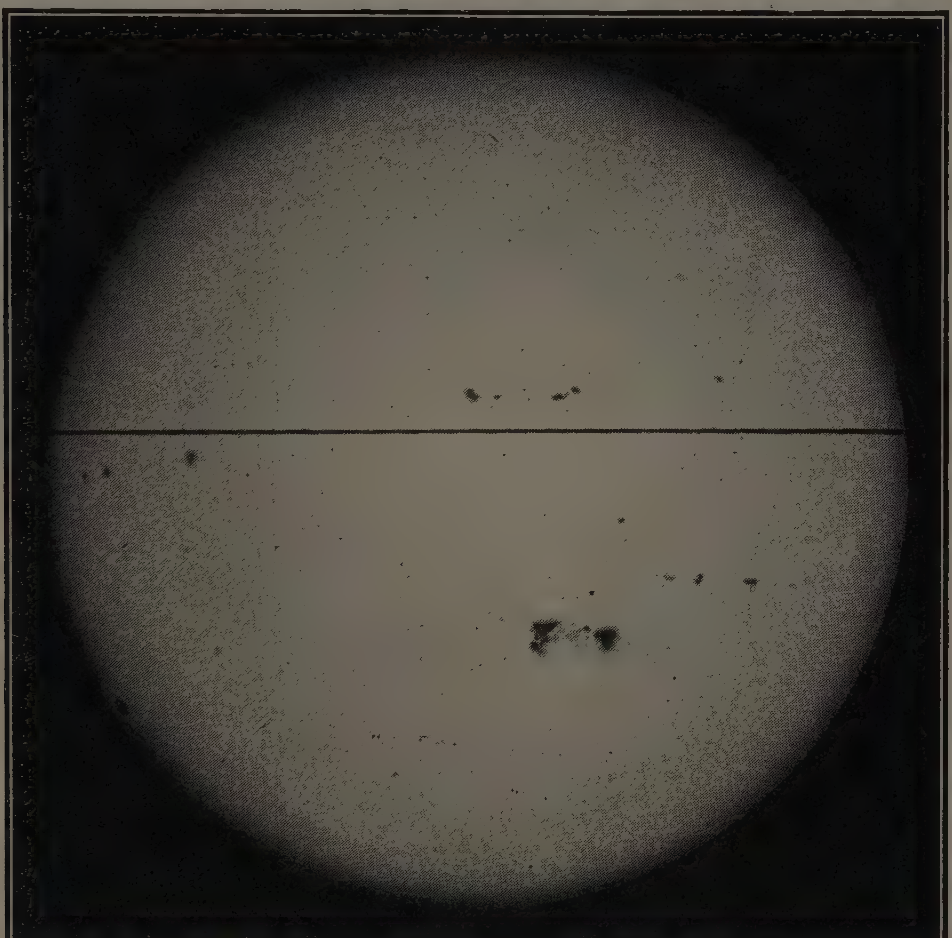


FIG. 97.—Direct photograph of the sun showing sun-spots, faculæ and absorption effect near edge. (*Photographed by Wilson at the Goodsell Observatory.*)

sure" and would expect the spectrum to consist of bright lines. Under ordinary conditions it is not possible to observe this because of the bright photosphere, but at the time of a total eclipse of the sun the moon's disc cuts off the photospheric light and for a second or two the bright lines of this layer can be observed. This spectrum is known as the "flash" spectrum from the sudden flashing out of the bright lines at the proper moment during the eclipse.

[1] Certain theoretical considerations support the view that the pressure limits are considerably lower than the values given.

Owing to the small depth of the layer and the distance of the sun it is not necessary to use a collimator on the spectrograph used to photograph the "flash." In consequence, the lines, instead of being straight, are curved and the length of the crescent is an indication of the height to which the element rises in the solar atmosphere. Figure 98 is a reproduction of the flash spectrum obtained by Frost of the Yerkes Observatory at the eclipse of 1900.

Most of the lines in the flash spectrum have their origin in the layer of gases within 2000 km (1200 miles) of the photosphere, but some of the lines, notably some belonging to hydrogen and calcium, have sources extending to 12,000 and 14,000 km above the photosphere respectively. The latter, however, belong to the chromosphere.

The actual depth of the reversing layer depends upon the definition of the term. Some assign a depth of 5000 km (3000 miles), while others hold that one-tenth this value is nearer the truth.

Fig. 98.—The flash spectrum at the eclipse of May 28, 1900. (*Photographed by Frost of the Yerkes Observatory.*)

At the Mt. Wilson Observatory it has been possible to photograph the lines of the flash spectrum without eclipse by using a large solar image of 46-cm (18-inch) diameter, but a very steady and large image is required. This method, however, does not give the elevations of the gases in the solar atmosphere.

Under the usual conditions the continuous spectrum of the photosphere is brighter than the lines of the "flash" and, except at the extreme edge of the image, the two are always in the same line. When this is the case, as it is over the disc of the sun in general, we have light from a source of a continuous spectrum passing through a gas under low pressure which gives bright lines when shining alone. In consequence, absorption takes place and instead of bright lines we have a continuous spectrum crossed by a multitude of dark lines. This absorption spectrum is the one obtained from the general disc of the sun, and is called the *solar spectrum* (Fig. 49). The many dark lines are the

evidence of the presence, in the region immediately above the photosphere, of many of the chemical elements. This region is called the *reversing layer*, because it produces bright instead of the usual dark lines.

The dark lines of the solar spectrum are often called the Fraunhofer lines because they were first studied and mapped by the German physicist, Fraunhofer, about a century ago.

178. Elements in the Sun.—A long and careful study has been made of the elements in the sun which betray their presence by dark lines in the solar spectrum.

The method is that of comparing the position of the dark lines with a bright-line spectrum of the various elements as obtained in the laboratory. Iron is responsible for about 2000 lines in the spectrum of the sun (Fig. 49), carbon over 200, calcium about 75, sodium 11, etc.

About 40 elements have thus far been identified as certainly existing in the sun, and there are about 12 whose existence is doubtful out of a total of 90 elements known in the laboratory. In general, the elements of low atomic weight are represented by more lines in the solar spectrum than those of high atomic weight, but there are exceptions to this rule.

The absence of an element in the spectrum of the sun is not a proof of its absence in that body. The conditions under which an element will emit its spectral lines differ among the elements, and it may be, therefore, that the missing elements are present, but the conditions in the reversing layer are not right for them to show absorption lines.

179. The Chromosphere.—The upper 10,000 km (6000 miles) of the solar atmosphere is called the *chromosphere*. The name was given because at the time of a total eclipse a narrow ring of rosy light is visible at a higher level than the reversing layer, and hence the name, which means "color sphere."

The spectrum of the chromosphere may be observed at any time with appropriate apparatus, and ordinarily consists of bright lines of calcium, helium and hydrogen. When there is a disturbance of the solar surface at the point of investigation, however, gases from lower levels are brought up and hundreds of bright lines become visible.

According to St. John and Babcock, the pressure in the chromosphere varies from about $1/10^4$ at the lower to $1/10^{13}$ atmospheres at the upper boundary. There is, however, no definite lower

boundary, as the transition from chromosphere to reversing layer is not abrupt and the two names used in describing the upper and lower levels of the solar atmosphere are merely a matter of convenience.

180. The Spectroheliograph.—This instrument consists of a spectrograph so mounted that it can be moved with respect to the image of the sun and the photographic plate. By means of a second slit, placed immediately in front of the plate, the light coming from only a single line of the spectrum is allowed to reach the sensitive film. At any instant therefore the impression obtained gives the relative intensities of the light in this line as distributed across the sun. By the motion of the instrument

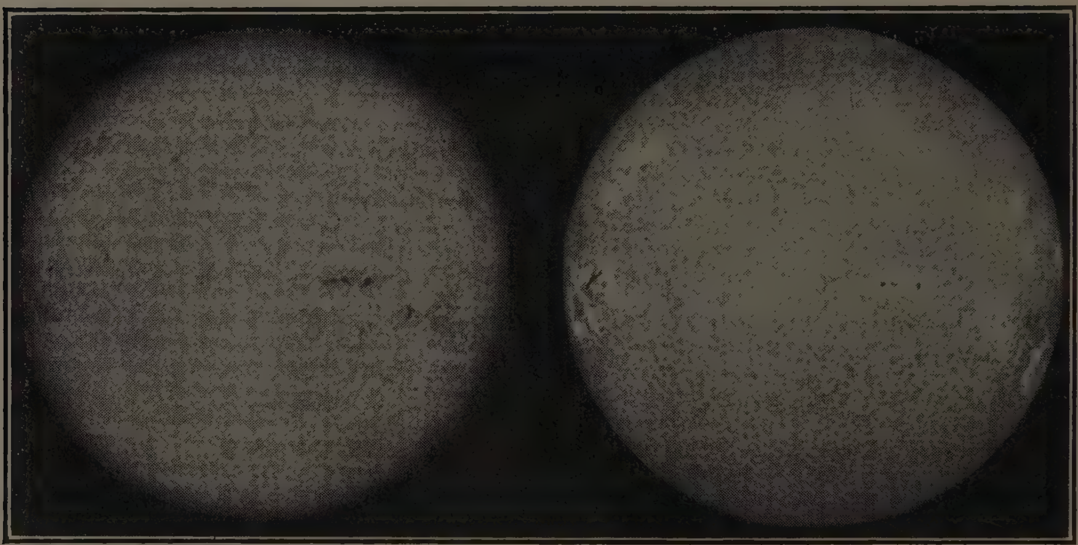


FIG. 99.—Spectroheliograms of the sun, showing the distribution of hydrogen (left) and calcium (right) in the solar atmosphere. (*Photographed at the Mt. Wilson Observatory.*)

across the image of the sun and also by moving it at the same rate with respect to the plate, a complete photograph of the sun is obtained showing the distribution across the sun of the element whose line has been used. Photographs thus obtained are called *spectroheliograms.*

The spectroheliograph was developed independently by Hale in this country and Deslandres in France about 1892. It is used especially for the study of the distribution of calcium and hydrogen in the sun's atmosphere and the photography of prominences. Lines of other elements than calcium and hydrogen can be used, but since other elements have less prominent lines in the solar spectrum the spectroheliograms are not so easily obtained.

Figure 99 shows spectroheliograms giving the distribution of calcium and hydrogen in the sun's atmosphere.

181. Prominences.—From time to time there may be observed above the level of the chromosphere immense clouds of luminous gases, which are called prominences. These vary in height from those which can just be detected to some which rise over 800,000 km (500,000 miles) above the solar surface. Elevations above 150,000 km are rare.

Two kinds of prominences are usually distinguished, the *quiescent* and the *eruptive.* The quiescent sort resemble in form the clouds usually seen in our own atmosphere (Fig. 100). They are

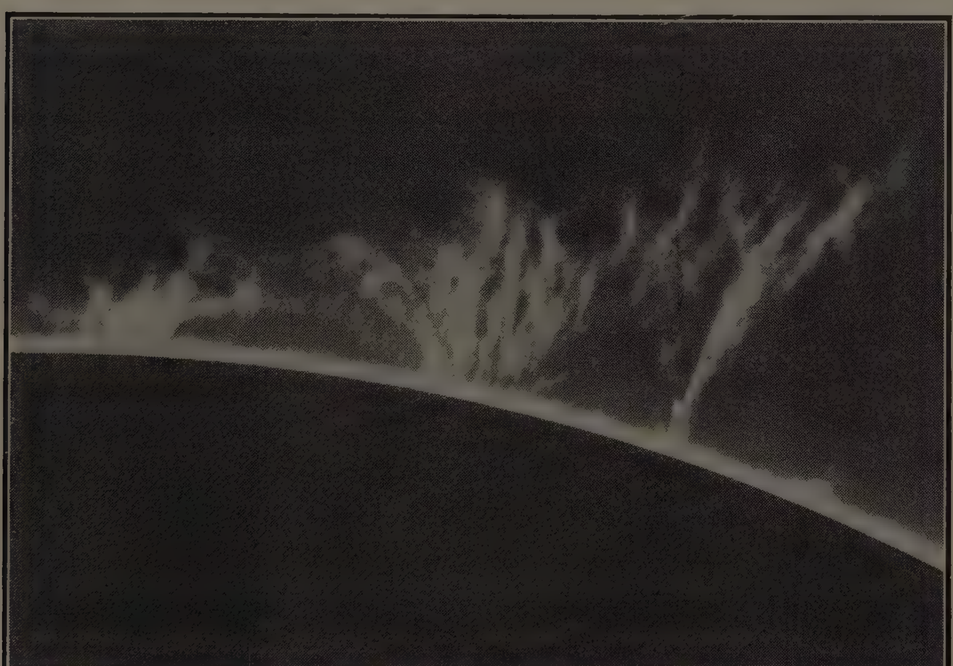


FIG. 100.—Quiescent prominence 128,000 km (80,000 miles) high. (*Photographed at the Mt. Wilson Observatory.*)

relatively long-lived, sometimes lasting several days. The eruptive prominences, on the other hand, last but a few hours, and, as the name implies, show high velocities and rapid changes of form (Fig. 101). Velocities exceeding 150 km (100 miles) per second are often noted and occasionally some as high as 300 km per second.

The spectrum of the quiescent prominences usually shows the presence of calcium, helium and hydrogen, but the eruptive prominences show, in addition, the presence of sodium, magnesium, barium, iron, titanium and some other elements.

Prominences may be found all around the edge of the sun, although they are more numerous between latitudes 45° north and south than elsewhere. The number visible at any one time varies from 25 or 30 to none. The complete absence of prominences usually occurs when sun-spots are absent, while they are present in considerable numbers when spots are numerous.

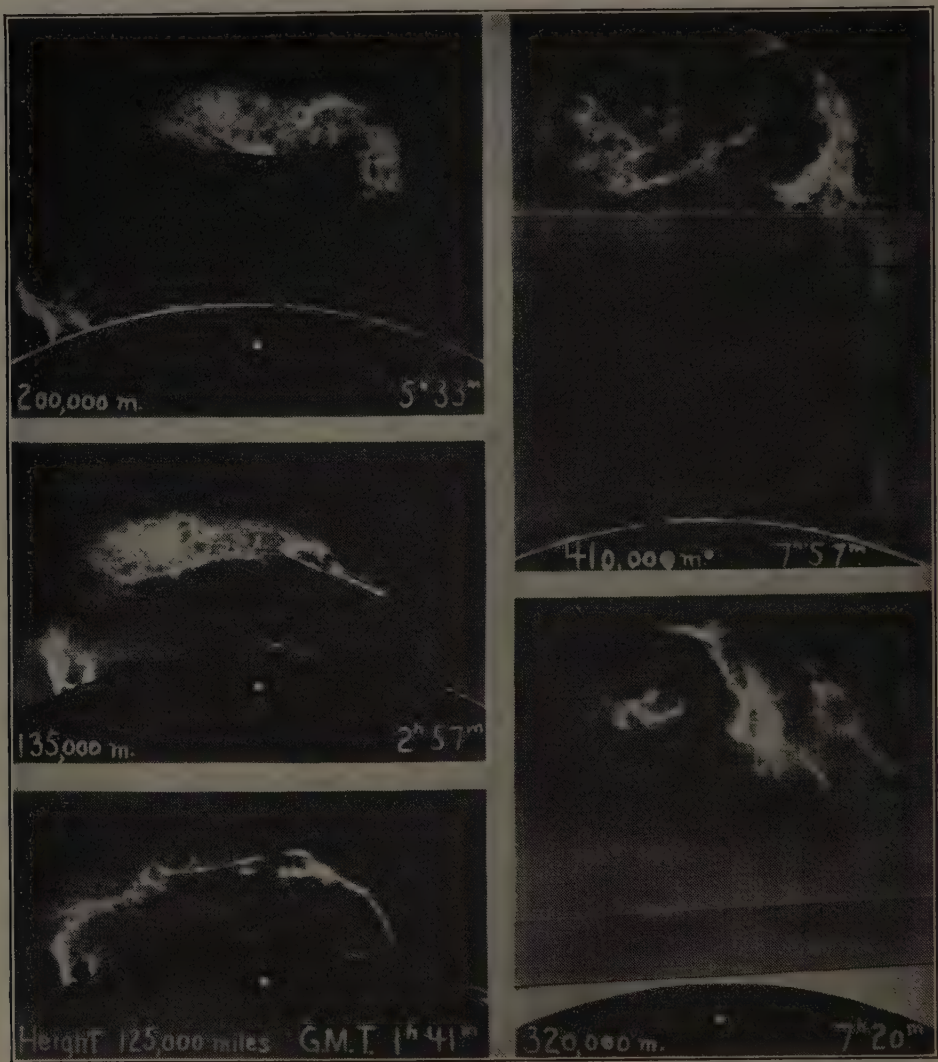


Fig. 101.—Series of spectroheliograms of an eruptive prominence May 29, 1919, showing increase in height from 125,000 to 410,000 miles in 5 hours, 39 minutes. The small white dot shows size of earth on the same scale. (*Photographed at the Yerkes Observatory.*)

Undoubtedly, prominences are present everywhere over the solar surface, but it is almost impossible to detect them elsewhere than at the edge.

182. Faculæ.—As stated in Sec. 176, bright regions called faculæ may be seen in the neighborhood of sun-spots. Similar regions are also frequently seen near the edge of the sun. They

appear to be elevated regions of the photosphere which, because of their elevation, lose less light by absorption than the general photospheric surface and thus become conspicuous.

183. Flocculi.—Hale's early study of the solar surface with the spectroheliograph showed many great clouds of luminous calcium vapor in the solar atmosphere. He called these *flocculi*. These are shown in Fig. 99 (right). Later, while working with hydrogen lines, he found dark clouds of hydrogen of great extent. In general, their appearance was so much like the bright calcium flocculi that they were also given the name flocculi. Hydrogen flocculi are shown in Fig. 99 (left).

184. The Corona.—At the time of a total eclipse of the sun there appears around the sun an exquisitely beautiful halo of

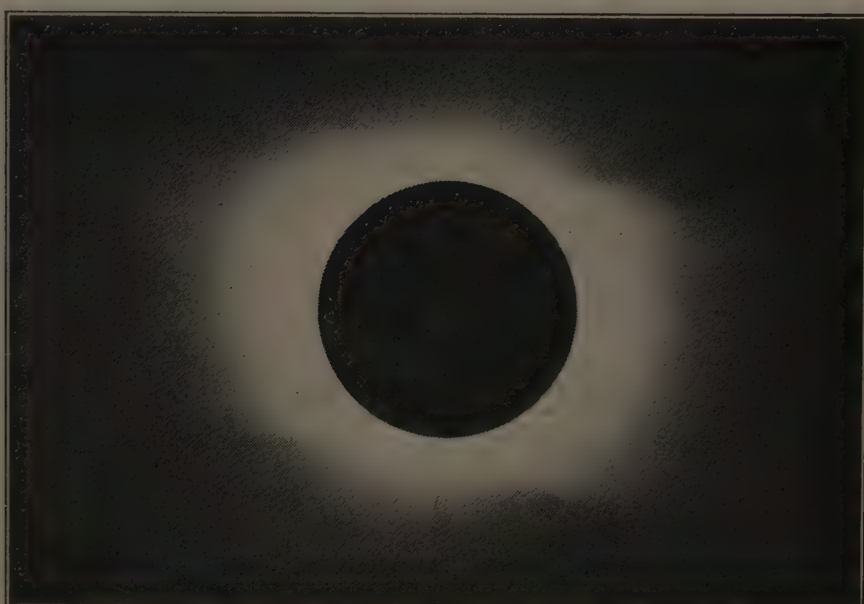


Fig. 102.—Solar corona at the eclipse of May 28, 1900, showing type at sun-spot minimum. (*Photographed by Wilson of the Goodsell Observatory.*)

pearly white light which is called the *corona*. Near the edge of the sun the corona is quite bright, but the brightness falls off quite rapidly with increasing distance. Thus far it has been impossible to see the corona except during a total solar eclipse.

The shape of the corona varies a great deal but, in general, at spot minimum there are long equatorial streamers and short polar rays, while at spot maximum the polar rays are longer and the equatorial ones shorter, so that the extension from the sun is approximately uniform in all directions. At spot maximum the corona extends about one solar diameter or less from the sun's edge, but at spot minimum equatorial streamers may extend outward several diameters (Figs. 102 and 103). At the eclipse

of 1878 two streamers were traced outward a distance of 10 diameters, or about 15,000,000 km (9,000,000 miles). So far as the author can find this is the maximum length of coronal streamers on record.

185. Motion in the Corona.—Deslandres and Campbell have each found indications, by means of the spectrograph, that the corona is in motion, but exact quantitative results are lacking. It is not known whether the corona rotates as a whole with the sun or not.

Photographs of the corona made at the eclipse of 1918 by the Lick and Swarthmore expeditions located in Washington and Colorado respectively show many details of the inner corona. An interval of 26 minutes separates the exposures. A study of these details by Miller shows some differences in the two photo-

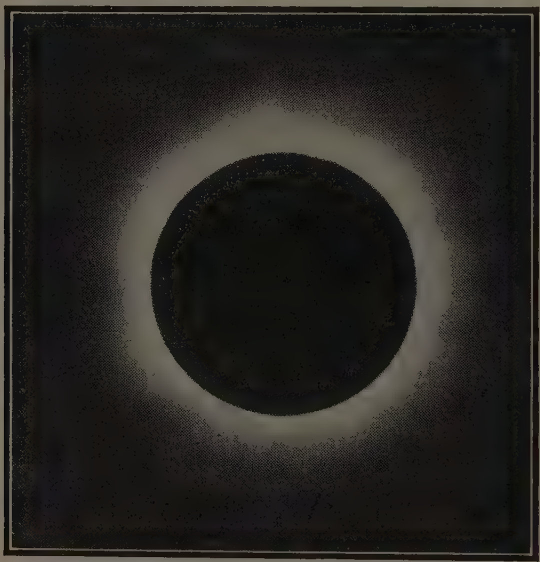


FIG. 103.—Solar corona at eclipse of Aug. 30, 1905, showing type at sun-spot maximum. (*Photographed by Campbell of the Lick Observatory.*)

graphs which indicate an outward motion in the interval between the exposures at the rate of 16 km (10 miles) per second.

186. Coronal Spectrum.—The spectrum of the corona appears to be composite. The dark lines of the solar spectrum are found, but the continuous background is brighter. This is interpreted to mean that there are particles reflecting the ordinary solar spectrum and that, in addition, there are some particles hot enough to give a continuous spectrum which is superposed on the absorption spectrum.

In addition to this there are a number of bright lines, especially one in the green at $\lambda 5303$, which have not been identified as

belonging to any known element. Provisionally, therefore, they are assigned to an unknown element which has been given the name *coronium*, as these lines have been found only in the corona. Theoretically, there is no place in the periodic table of chemical elements for coronium, but a discussion of this point is beyond the scope of this book. It may be that the substance we call coronium is a known element giving the bright coronal lines under the conditions obtaining in the corona but which have not yet been duplicated in the laboratory. The intensity of the green coronal line varies at different eclipses.

187. Nature of the Corona.—The nature of the corona is still largely a matter of speculation, since the actual time the corona has been studied by modern methods is less than 1 hour. We must, therefore, be content with a statement of some of the facts and possible inferences.

We know that the density of the corona, even close to the sun, is exceedingly low. The great comets of 1843 and 1882 almost grazed the sun's surface and at the time were moving with a velocity of about 500 km (300 miles) per second. Both comets went through at least 1,000,000 km of the corona at this great velocity without suffering the slightest appreciable retardation.

There must be a few solid or liquid particles which reflect the sun's light in order to account for the Fraunhofer lines in the coronal spectrum. There must also be the atoms of the substance called coronium which give the bright lines of the spectrum. The cause of the emission of light is likely to be found in electrons driven off from the sun.

The material of the corona undoubtedly has its source in the sun, but whether it is driven outward and ultimately dissipated into space or whether it is held more or less in suspension above the sun's surface is not known. It is probable that the force in either event is radiation pressure.

The total brightness of the corona is small. Observations by Stebbins and Kunz at the eclipses of 1918 and 1925 by means of the photoelectric cell, and by Pettit and Nicholson at the eclipse of 1925 by means of the thermocouple, agree in making the total light of the corona almost exactly one-half that of the full moon.

CHAPTER X

ECLIPSES

ECLIPSES OF THE MOON

188. Geometry of the Lunar Eclipse.—An eclipse of the moon occurs when the moon passes into the earth's shadow. In Fig. 104 let the plane of the page represent the plane of the ecliptic, S the sun, E the earth, M the moon and the dotted line HJ a portion of the moon's orbit around the earth.

From the figure it is clear that within the region BDG we have a cone-shaped space which is occupied by the earth's shadow and from which the sunlight is wholly excluded. In the region around the cone like JBD the sunlight is only partially excluded. The shadow cone is called the *umbra* and the surrounding region,

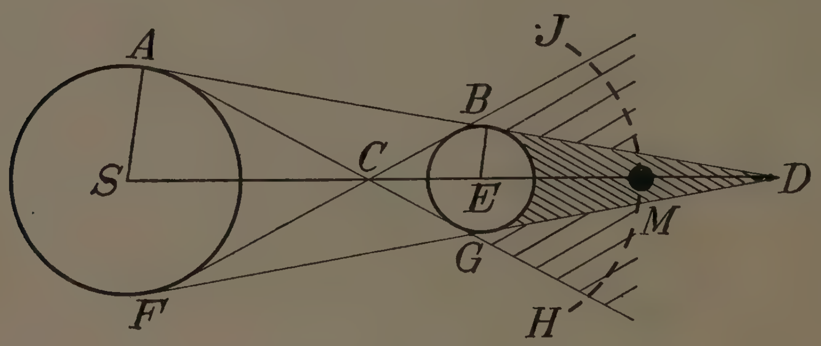


Fig. 104.—Eclipse of the moon.

BJD, the *penumbra.* The boundary between umbra and penumbra is not sharp because the earth's atmosphere forms no definite shadow.

189. Length and Diameter of the Earth's Shadow.—The mean length of the earth's shadow cone is approximately 1,379,000 km (857,000 miles), a value easily calculated by the use of the similar right triangles ASD. and BED. The diameter of the shadow at the moon's mean distance is about 9200 km (5700 miles). The length of the shadow varies slightly owing to the earth's varying distance from the sun. The diameter at the moon will vary for the same reason as well as because of the moon's varying

distance from the earth. Both variations are small and can be disregarded in an elementary discussion.

190. Lunar Eclipse Limits.—If the moon's orbit lay in the plane of the ecliptic there would be an eclipse at each full moon but, since this is not the case, eclipses occur only under certain conditions. In Fig. 105 let NC represent the plane of the ecliptic, NB the plane of the moon's orbit, N the node[1] of the moon's orbit, M the moon and E the earth's shadow at the moon's distance. From the figure it is evident that if full moon and shadow were farther from the node than indicated there would be no eclipse, if nearer an eclipse would be certain. Hence the shadow must be near a node at the time of full moon in order that an eclipse may occur. This distance from the node is called the *lunar eclipse limit.* This limit is not constant owing

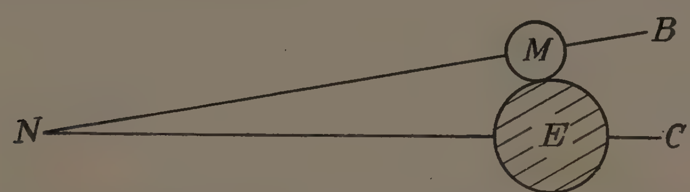


Fig. 105.—Lunar eclipse limits. E is the earth's shadow and M the moon.

to the slight variation in the inclination of the moon's orbit and to the varying diameter of the shadow at the moon's distance. Hence it is customary to give maximum and minimum values such that if the shadow's distance from the node exceeds the maximum no eclipse is possible while if less than the minimum an eclipse is certain. These maximum and minimum values are 12°.2 and 9°.5 respectively.[2]

191. Duration of Lunar Eclipse.—If the eclipse occurs when the shadow and the full moon are quite near one of the nodes of the moon's orbit, the moon will pass entirely into the shadow. This is known as a *total eclipse.* If the entire body of the moon does not pass into the shadow a *partial eclipse* occurs.

In Fig. 106 the numbers 1, 2, 3 and 4 represent four positions of the moon with respect to the shadow. Position 1 is called *first contact,* position 2 *second contact,* etc.

[1] The intersection of the moon's orbit with the plane of the ecliptic is called the *node*.

[2] As usually defined, the lunar ecliptic limits are the distances of the sun from the node opposite N. The values are the same since the two nodes are precisely opposite and the sun is always just 180° from E.

When the moon passes through the center of the shadow the time from first to fourth contact is about 4 hours; from second to third contact about 2 hours. If the eclipse is not central, the duration will be less and less until a small partial eclipse may be only of a moment's duration.

192. Phenomena of a Lunar Eclipse.—For some time, possibly half an hour, before the moon reaches the shadow the eastern side of the moon may be seen to darken gradually. When it reaches the shadow the darkening is very marked, looking almost black by contrast. The edge of the shadow appears sharp to the unaided eye but even in a field-glass the sharpness disappears. If the eclipse is total the surface of the moon appears of a dull-orange hue, the intensity varying considerably from one eclipse to another. This is caused by the refraction of the sun's rays

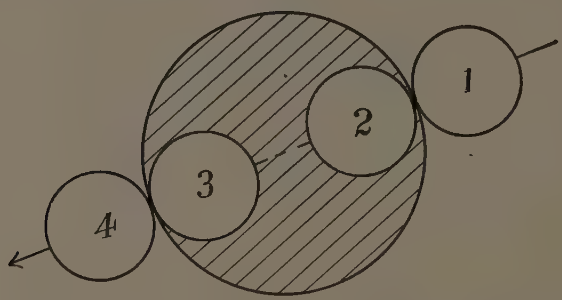


Fig. 106.—Contacts of moon with earth's shadow.

into the shadow by the earth's atmosphere. The rays most strongly refracted have passed through a large mass of air, and accordingly have lost their blue light. If that portion of the atmosphere through which the sun's rays pass is filled with clouds, very little light may be refracted into the shadow. This occurred at the total eclipse of Oct. 4, 1884, when the moon's disc was invisible to the naked eye.

193. Visibility of Lunar Eclipses.—From Fig. 104 it is clear that an eclipse of the moon is visible over an entire hemisphere of the earth. The various phases of the eclipse will also occur at the same instant and be visible wherever the moon is above the horizon. If the eclipse is of long duration it will be visible over considerably more than a hemisphere because of the rotation of the earth.

ECLIPSES OF THE SUN

194. Geometry of the Solar Eclipse.—An eclipse of the sun occurs when, at new moon, the moon passes so near the line between

earth and sun as to cut off some or all of the sun's light. In Fig. 107 let S represent the sun, M the moon and E the earth. The moon's shadow is cone-shaped, with the base of the cone at the moon. (If the shadow cone touches the earth an observer within the cone will find all the sunlight cut off, as at ab. An observer in the region bc will see only part of the sun's disc hidden by the moon. For the first observer the eclipse will be *total*, for the second *partial*.) The shadow cone itself is called the *umbra*, while the portion surrounding it, as cdb, is called the *penumbra*.

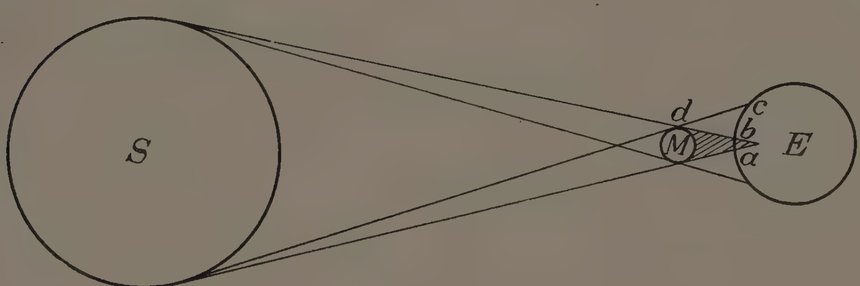


FIG. 107.—Eclipse of the sun.

195. Length and Diameter of Moon's Shadow.—The length of the moon's shadow varies from about 367,000 to 380,000 km (228,000 to 236,000 miles). Since its distance from the earth varies from 357,000 to 407,000 km, it is clear that sometimes the tip of the shadow may not reach the earth at all. If this is the case an observer within the prolongation of the cone of the shadow will see a narrow ring of sunlight around the body of the moon. Such an eclipse is an *annular eclipse.*

The maximum cross-section of the moon's shadow at the earth is 269 km (167 miles), but since the earth's surface is seldom perpendicular to the axis of the shadow cone the outline of the shadow on the earth will, in general, be elliptical and of greater dimensions than the cross-section.

196. Solar Eclipse Limits.—Because of the inclination of the moon's orbit to the plane of the ecliptic the sun is not obscured at the time of each new moon. Only when sun and moon are near one of the nodes of the moon's orbit is an eclipse possible. Hence the distance of the sun from the moon's node at the time of new moon is the determining factor in much the same way as in the case of a lunar eclipse (Sec. 190). For an eclipse of the sun to be certain, the sun must be within 15°.2 of the node at the

time of new moon, while if more than 18°.5 from the node an eclipse is impossible. For the eclipse to be central, either total or annular, the corresponding limits are 9°.9 and 11°.8 respectively.

197. Velocity of Moon's Shadow.—The velocity of the tip of the moon's shadow with respect to the earth's center is, of course, essentially equal to the moon's velocity in her orbit, 3370 km (2100 miles) per hour. The velocity with respect to the earth's surface, however, depends upon the region touched by the shadow, since the moon's motion and the earth's rotation are both eastward. At the poles of the earth the rotation effect is negligible, hence the shadow passes at the rate of 3370 km per hour. At the equator, however, the earth's eastward rotation is about 1675 km (1040 miles) per hour, so that the shadow moves at the rate of 1695 km (3370 minus 1675) per hour for an observer located there. At latitudes 30° and 60° the velocity of the shadow will be 1930 and 2575 km (1200 and 1600 miles) per hour[1] respectively.

198. Duration of Total Eclipse.—If we know the velocity of the shadow and its width for any particular point on the earth it is a simple matter to find the duration of the eclipse for that point. Under the most favorable conditions possible the duration of a total eclipse is a little less than 8 minutes. Such conditions, however, do not occur more than once in some thousands of years. The average duration is about 3 minutes. If the tip of the shadow cone just grazes the earth, the duration will be only an instant at the point of contact.

199. Visibility of Total Eclipses.—At any particular instant a total eclipse is visible only to those within the small area of the earth's surface on which the shadow falls. The elliptical outline of the shadow is carried across the surface of the earth with the velocity given in Sec. 197. The narrow strip of the surface along which the shadow passes is called the *path* of the eclipse, or the *shadow path.* The width of the path averages about 160 km (100 miles) in the temperate and torrid zones, although, under favorable circumstances, greater widths are possible.

The eclipse may be observed as total only by those within the narrow shadow path. For this reason a total eclipse of the sun is a very rare phenomenon at any particular place on the

[1] These velocities for regions at some distance from the poles hold only when the sun is on the meridian at the time of the eclipse. If the eclipse occurs near sunrise or sunset the velocity will be considerably higher.

earth. Young estimated that at any one station a total eclipse will be visible once in 360 years, in the long run.

Outside the shadow path and within the limits of the penumbra the eclipse will be seen as partial.

200. Phenomena of Total Solar Eclipse.—About 1 hour before the total phase the moon may be seen gradually encroaching on the disc of the sun. About 15 minutes before totality the light wanes perceptibly and the landscape takes on peculiar color tones not usually seen. Animals show signs of uneasiness. The por-

FIG. 108.—The Lick Observatory eclipse station at Goldendale, Wash., for the total solar eclipse of June 8, 1918.

tion of the sun remaining visible is a narrow crescent and crescent-shaped images may be seen on the ground where the sunlight filters through the foliage of trees or other small apertures. During the last 2 or 3 minutes before the sun disappears peculiar wave-like shadows, called shadow bands, may usually be seen moving over the ground. These also appear after totality.[1]

A few seconds before totality the brighter parts of the corona become visible and an observer who has a clear horizon toward the west may note the approach of the shadow.

[1] Shadow bands have occasionally been seen during totality.

At the beginning of totality the corona appears in all its beauty. At the same time solar prominences may be seen projecting outward beyond the edge of the moon and some of the planets and brighter stars appear. The darkness is usually very marked, but a large watch face can be read with comparative ease. A fall of several degrees in the air temperature is also common.

At the end of totality the sudden return of the sunlight brings a feeling of relief, the corona and prominences fade away, the shadow bands again become visible for a minute or two, and, finally, in about an hour, the moon passes off the sun's disc.

201. Eclipse Problems.—There are various problems which can be attacked only at the time of a total eclipse. Some of these are the corona, the flash spectrum for determining the heights at which the various elements give their characteristic lines, the search for small planets inside the orbit of Mercury, the exact path of totality for checking the position of the moon and the deviation of a ray of light passing close to the sun (Sec. 202).

It has been estimated that if an observer were to observe all total eclipses which occur in reasonably accessible regions of the earth in half a century, and taking into consideration the possibility of cloudy weather, he would probably have less than a total of 1 hour in which to carry on observations during totality. Considering the limited time during which total eclipses have been observed with modern equipment, it is evident that every reasonable opportunity must be used to study the eclipsed sun if progress is to be made in solving eclipse problems.

202. The Einstein Eclipse Problem.—Einstein had predicted, on the basis of his theory of gravitation, that a beam of light just grazing the edge of the sun would be deflected through an angle of $1''.74$, the path of the beam becoming concave toward the sun, and that the deflection would vary inversely as the distance of the beam from the sun's center. The only way to test the prediction consists in photographing the stars which can be seen in the immediate neighborhood of the sun during a total eclipse and comparing these photographs with similar ones taken of the same star field when the sun is not there. The deflection, if found, would be of such a nature that the stars would be farther from the center on the eclipse plates than on the others.

The first test of the prediction was made at the eclipse of 1919 by two English expeditions under Eddington and Crommelin in Africa and South America, respectively. After rejecting poor

plates the others yielded values of 1″.61 and 1″.98 for the two sets of plates when the measures were reduced to the edge of the sun.

The next test was made by parties from the Lick Observatory and from Canada at the eclipse of Sept. 21, 1922, in Australia. The results of the Canadian party, from quite limited material, gave a value of 1″.78 (mean of three solutions), and the Lick party, from much more extensive material, obtained 1″.72—values very close to the predicted amount.

203. The Shadow Bands.—These wavering shadows, which are usually but not always seen immediately before and just after totality, within the eclipse path were also observed outside the path at the eclipse of Jan. 24, 1925. From all the observations available it appears that these shadows are produced in our own atmosphere, but the exact conditions necessary to produce them are not wholly clear, since they have not been seen at every eclipse.

204. Number of Eclipses.—Since eclipses of sun and moon are possible only when the sun is near one of the nodes of the moon's orbit, eclipses, in general, will occur at intervals of about 6 months. Since the lunar eclipse limits are smaller than the solar, it is possible that no eclipses of the moon will occur in any calendar year. Two solar eclipses must occur under these conditions, however. In this century there are 14 years when only two solar and no lunar eclipses take place. Under the most favorable circumstances there may be as many as seven eclipses, two of the moon and five of the sun or three of the moon and four of the sun, in any one year. During the remainder of the twentieth century the first combination will occur only in 1935 and the second in 1982.

From 1901 to 2000 A.D. there will be a total of 375 eclipses, according to Oppolzer's "Canon der Finsternisse," 228 of the sun and 147 of the moon, an average of nearly four per year.

205. The Saros.—Because of the revolution of the moon's nodes westward at the rate of 19°.5 annually, the sun meets the same node in 346.62 days. This interval is called the *eclipse year*. The relation between this and certain values is as follows:

	Days
242 returns of moon to a particular node	6585.36
19 returns of sun to the same node	6585.78
223 synodic months	6585.32

In the interval of 6585 and a fraction days we therefore expect sun and moon to return to approximately the same positions with respect to one of the nodes of the moon's orbit. In consequence, if an eclipse has occurred at any time, we may expect a similar eclipse to occur again at the end of this interval. If we note a series of eclipses in the interval we may expect an analogous series in the following interval.

This recurrence of eclipses was known to the ancients and the time interval of 223 synodic months or 18 years 10 or 11 days (depending on how many leap years occur) was called the *saros*.

The return of the same eclipse will not be for the same region on the earth, owing to the ⅓ day over the 6585 days. The earth will have turned about 120° in this time, so that the eclipse will take place about 120° of longitude farther west than before. The total eclipse of the sun of Sept. 10, 1923, was the return of a similar eclipse of Aug. 30, 1905. The latter was well located for observation in Spain and its repetition in California one saros later.

A lunar eclipse repeats itself 48 or 49 times before the small deviations from exact commensurability eliminate it entirely. Such a series lasts about 865 years. A solar eclipse also has from 68 to 75 returns, the series lasting about 1260 years, according to Young.

The total number of eclipses in one saros is about 70, of which number 41 are usually solar and 29 lunar. Of the solar eclipses, 14 are partial, 17 annular and 10 total.

CHAPTER XI

THE PLANETARY SYSTEM

The solar system consists of the sun, planets and satellites, asteroids, comets and such meteor swarms as are moving under the gravitation of the sun. This system forms a unit, which, so far as we know, is unique in the universe.

206. The Planets—Definition and Names.—The term *planet* is usually applied only to any one of the eight larger bodies which, like the earth, move about the sun. Their names, in order of distance from the sun, are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.

According to size, the eight planets fall into two groups, the first four usually being termed the *terrestrial planets*, because they are not very different from the earth in size, and the last four the *major planets*, because, as a group, they are very much larger than the first four.

There are, in addition to the eight known planets, many small bodies called *minor planets* or *asteroids*, which are also moving about the sun. Over a thousand of these, having diameters of 800 km (500 miles) or less, have been discovered in the last 125 years. In many ways they resemble the large planets, but as a group they show a marked difference.

In our study of the planets we shall find many things to consider, such as their apparent and real motions in the sky, their distances from the sun, the eccentricities of their orbits and the inclinations of the orbit planes to the plane of the ecliptic, their periods of revolution about the sun, their diameters, masses, densities, rotation periods, physical conditions, satellite systems, etc.

The terms *rotation* and *revolution* are ordinarily used as synonyms, but in astronomy it is agreed to use *rotation* only when it refers to the turning of a body about an axis through its center of mass, while *revolution* is applied to the motion of one body about another. Thus, the earth rotates on its axis in a day but it revolves around the sun in a year.

207. Inner and Outer Planets.—There is a second way of grouping the planets—those whose orbits lie inside and those whose orbits lie outside the earth's orbit. Mercury and Venus belong to the first group, and Mars, Jupiter, Saturn, Uranus and Neptune to the second. All asteroid orbits known also lie outside the orbit of the earth. Planets and asteroids move about the sun in the same direction, from west to east, and at velocities which decrease with increasing distance from the sun.

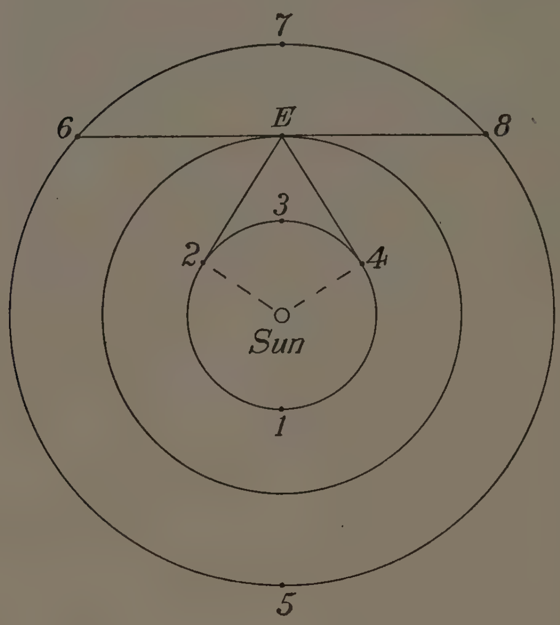


FIG. 109.—Planetary elongations.

208. Positions Relative to Earth and Sun.—In Fig. 109 let the inner circle represent the orbit of an inner planet, the second the earth's orbit and the third the orbit of an outer planet.

The *elongation* of a planet is the angle at the earth between the lines drawn to planet and sun.

If the earth is at E when the inner planet is at 1, the planet is said to be in *superior conjunction*, when at 3 in *inferior conjunction*. When at 2 or 4 it is at *greatest elongation*.[1] The elongations are either *east* or *west*, depending upon the direction of the planet from the sun.

The outer planet is in *conjunction* when at 5, in *opposition* when at 7 and in *quadrature* when its elongation is 90° as at 6 or 8.

209. Apparent Motions of the Planets Among the Stars.—In Fig. 110 let the outer circle represent the earth's orbit and the inner circle the orbit of an inner planet. If the planet is at inferior conjunction it will be at P_1 when the earth is at E_1. Later the planet reaches greatest western elongation at P_2 when the earth is at E_2 and when the earth is at E_3, the planet will be at superior conjunction at P_3. Still later will come eastern elongation with planet and earth at P_4 and E_4 respectively. Finally, inferior conjunction occurs with the two bodies at P_5 and E_5. This series of positions will appear from the earth as a slow vibration of the planet, first to one side and then to the

[1] The lines $E2$ and $E4$ are tangents to the orbit of the inner planet and the angles 2 and 4 are approximately right angles.

other of the sun. The motion of the planet, when combined with the sun's motion eastward among the stars, gives a comparatively complicated movement of the planet among the stars.

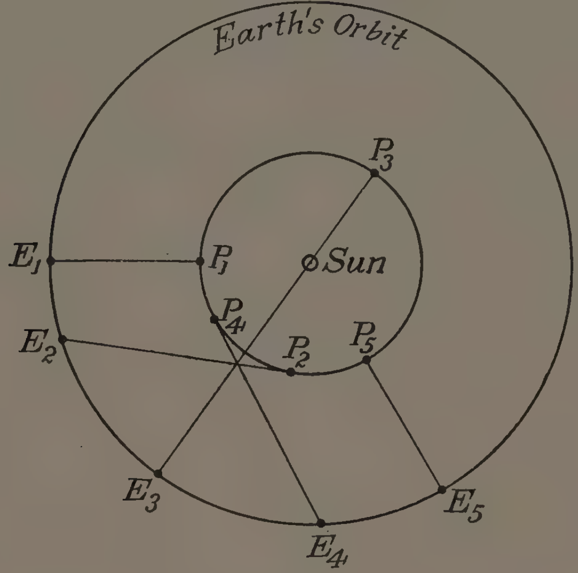


FIG. 110.—Positions of an inner planet as seen from the earth.

For the outer planets a different series of positions will be found. Beginning at conjunction E_1P_1 (Fig. 111) the planet will appear to move gradually eastward and at E_2P_2 quadrature will

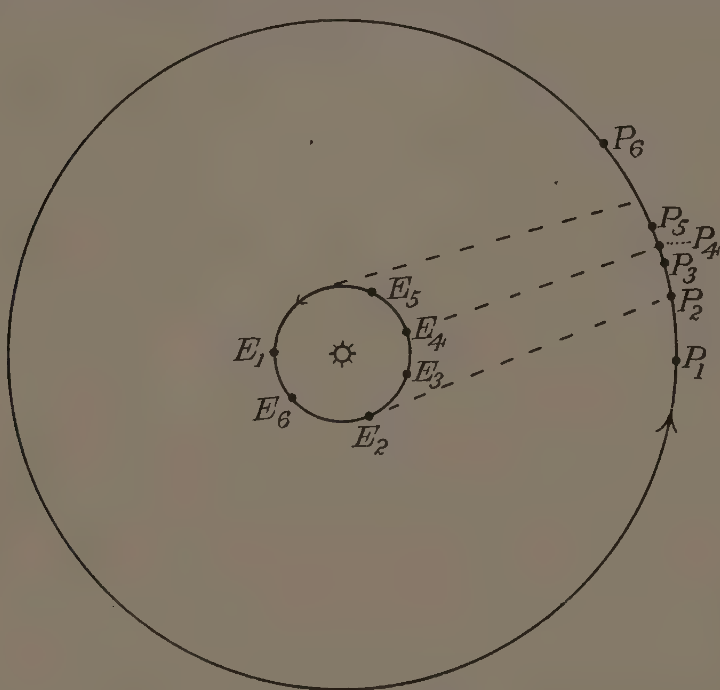


FIG. 111.—Positions of an outer planet as seen from the earth.

occur. After quadrature the planet will continue to move eastward until it reaches P_3, a short time before opposition. From this time onward, past opposition E_4P_4, and until position E_5P_5

the EP line will swing westward, owing to the earth's greater orbital velocity. After positions 5 the planet's apparent motion will again be eastward until and after conjunction E_6P_6. A planet is said to have *direct motion* when it moves eastward and *retrograde motion* when it moves westward among the stars as seen from the earth.

210. The Astronomical Unit.—The mile is too small a unit for measuring planetary distances. In consequence a much larger unit, the mean distance from earth to sun, is now in general use and is called the *astronomical unit.* Its length is 149,504,200 km (92,897,400 miles) according to the best determinations, but this is still uncertain by some thousands of kilometers. This unit will be used in stating distances in the solar system.

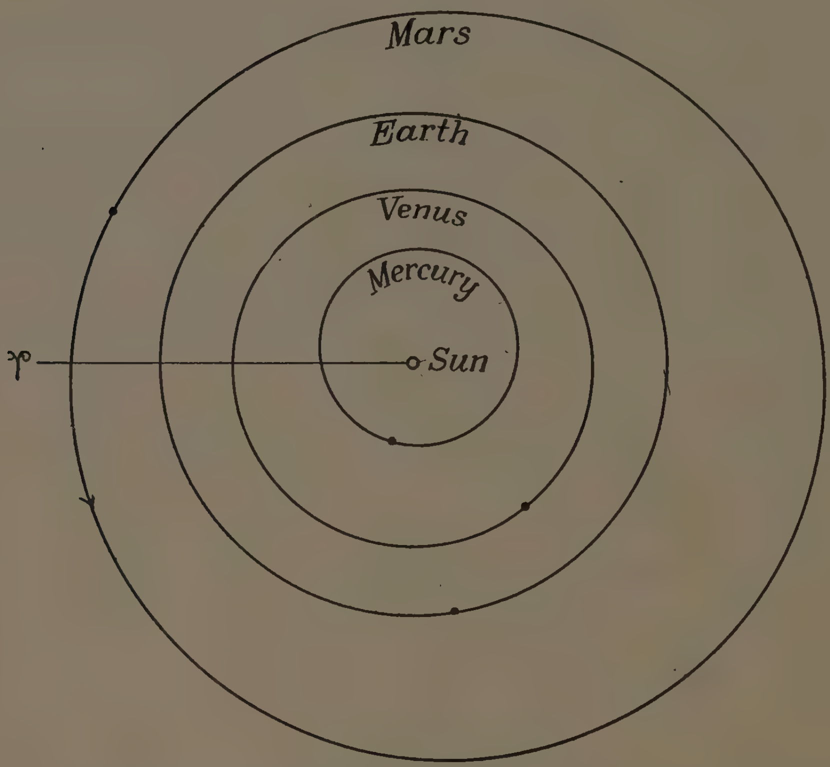


FIG. 112.—Orbits of the four planets nearest the sun. (*Perihelion ptsino marked by dots.*)

211. Planetary Distances.—The mean distances of the planets from the sun vary from 0.387 for Mercury to 30.071 for Neptune. Figure 112 shows the relative dimensions of the orbits of the four inner planets and Fig. 113 similarly the orbits from the earth outward.

The orbits of the asteroids, in general, lie between those of Jupiter and Mars.

212. The Bode-Titius Law.—In 1772, Bode brought to the general attention of the astronomical world a series of numbers which had been discovered by Titius six years earlier. This series is usually called *Bode's law,* and may be stated as follows:

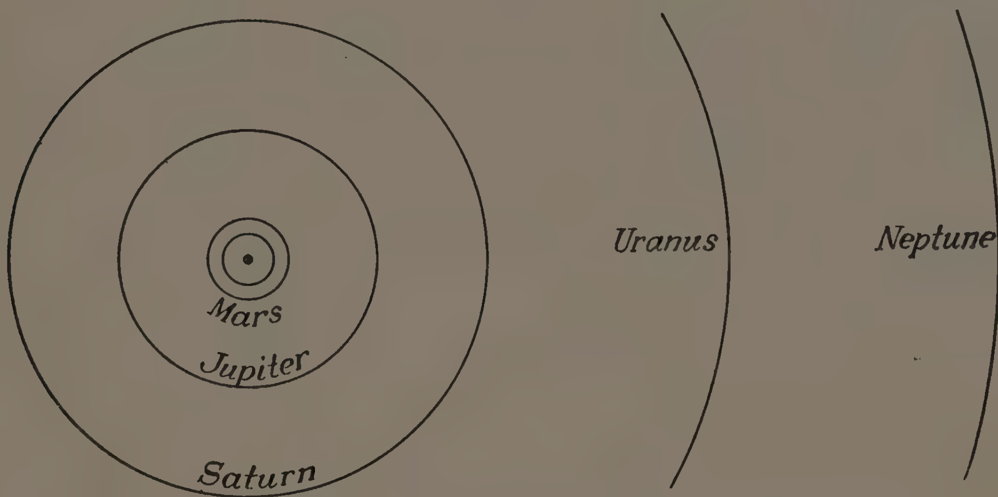


FIG. 113.—Orbits of the planets from Earth to Neptune.

If we write a series of 4's and to the second 4 add 3, to the next 6, to the next 12, etc., we obtain a series of numbers which represent approximately the relative distances of the planets from the sun.

4	4	4	4	4	4	4	4	4
	3	6	12	24	48	96	192	384
4	7	10	16	28	52	100	196	388

Table V gives these numbers divided by 10 and the actual mean distances for comparison.

TABLE V

Planet	Bode's law	Actual distance
Mercury	0.4	0.387
Venus	0.7	0.723
Earth	1.0	1.000
Mars	1.6	1.524
Asteroids	2.8	1.5–5.3
Jupiter	5.2	5.203
Saturn	10.0	9.539
Uranus	19.6	19.191
Neptune	38.8	30.071

There is no physical reason known underlying Bode's law and it seems likely that it is merely a chance arrangement of numbers which breaks down completely for Neptune.

213. The Orbits.—The orbits of the planets are all ellipses with moderate eccentricities varying from 0.007 for Venus to 0.206 for Mercury.

The orbits also lie nearly in the same plane. Using the plane of the earth's orbit as the reference plane, the orbit of Mercury makes the greatest angle and this amounts to only 7° 0′.

In comparison with the orbits of the planets the asteroid orbits have both greater eccentricities and inclinations. Thus, as an extreme case, the orbit of the asteroid Hidalgo (944) has an eccentricity of 0.653 and an inclination to the plane of the ecliptic of 43°.

214. Period.—A planet has two periods of revolution, a sidereal period and a synodic period. The *sidereal period* is the time required by the planet to complete one revolution about the sun with reference to the stars. The *synodic period* is the time required from any elongation to the same elongation next following, such as from superior conjunction to superior conjunction for an inner planet or from opposition to opposition for an outer one.

215. Kepler's Laws.—Tycho Brahe, the last great astronomer before the invention of the telescope, had accumulated a great mass of observations of planetary positions. His pupil, Kepler, spent many years in a careful study of these observations, and during this period announced the discovery of three laws of planetary motion now known as *Kepler's laws*. These are as follows:

1. *The orbit of every planet is an ellipse with the sun at one focus.*
2. *The radius vector of a planet sweeps over equal areas in equal times.*
3. *The cubes of the mean distances of the planets from the sun are proportional to the squares of their sidereal periods.*

1. From the historical standpoint the first law is the most important. From the earliest times until Kepler it had been assumed that the orbits of the planets had to be of a circular character because the circle was the only perfect curve and therefore the only one in which heavenly bodies could possibly move. Ptolemy, one of the great astronomers of antiquity, had assumed that all the heavenly bodies revolved about the earth as a center

and had built up (about A.D. 150) an elaborate system of circles to explain the motion of the planets. His system held sway until Copernicus, in 1543, published his great work "De Revolutionibus Orbium Coelestium," in which he showed that the sun was the center of the planetary system and that the apparent rotation of the heavens could be explained on the assumption that the earth rotated on its axis. Copernicus, however, still held to circular planetary orbits, although he found it necessary to put the sun out of center and it remained for Kepler to discover the real shape.

2. We have already considered this under the Law of Areas (Sec. 130).

3. As an illustration of the third law, let us compare the earth and Neptune and determine the period of the latter. The law may be applied as follows:

$$\frac{(\text{Earth's distance})^3}{(\text{Neptune's distance})^3} = \frac{(\text{Earth's period})^2}{(\text{Neptune's period})^2}.$$

This may be simplified by using periods in years and distances in astronomical units. The proportion may then be written

$$\frac{1^3}{30^3} = \frac{1^2}{x^2}.$$

Hence $x^2 = 30^3$ years $= 27{,}000$ years, whence $x = 164.2$. The actual value is 164.8 years, which value will be more nearly obtained if, instead of using the approximation of 30 for Neptune's distance, we had used 30.07. The law as stated, however, does not hold absolutely except for a planet of negligible mass.

216. Elements of an Orbit.—In the consideration of an orbit there are certain constants which are termed the *elements* of the orbit. These define the shape and the size of the orbit, its inclination to the plane of the ecliptic, the direction of the intersection of the orbit plane with the plane of the ecliptic, the direction of the perihelion point from the sun, the position of the planet in the orbit at a definite time and the sidereal period. By means of these elements the position of the planet can be calculated for any time, past or future, if the elements are accurate and as long as they are not changed by perturbations. Figure 114 illustrates the geometrical relations.

In the figure the plane of the orbit makes an angle with the plane of the ecliptic, the intersection of the two planes being along the line CD, which is called the *line of nodes*. The point D is

called the *ascending node* and the point C the *descending node*,[1] since the planet when passing D goes to the northern side of the ecliptic and when passing C to the southern side. Since the sun S is in the plane of the planet's orbit as well as in the plane of the ecliptic, it will be on the line of nodes. The line AP represents the major axis of the orbit and the line $S♈$ the direction of the vernal equinox from the sun. B is the midpoint of the major axis.

The *eccentricity* of the orbit e is the ratio of BS to BP and defines the shape.

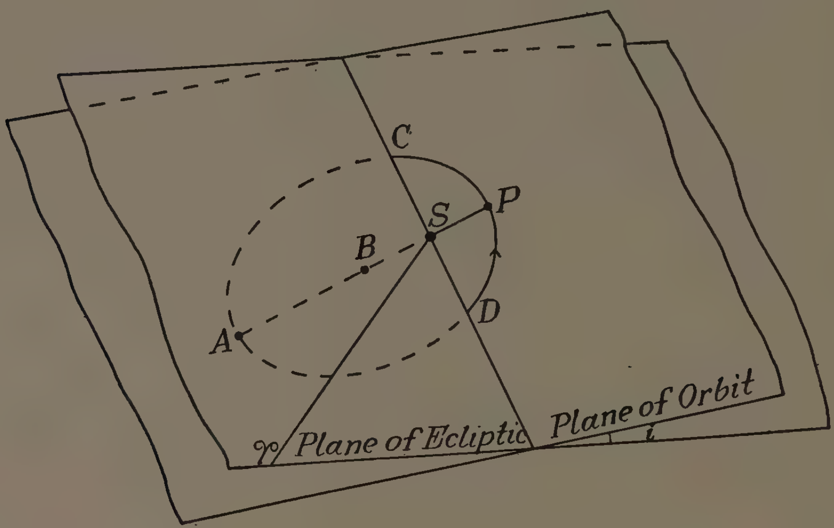


FIG. 114.—The elements of a planetary orbit.

The length of the *semi-major axis* BP determines the size of the orbit and is usually denoted by a. It is also known as the *mean distance* of a planet from the sun.

The angle between the planes of the orbit and ecliptic is called the inclination i.

The angle $♈SD$ is called the *longitude of the ascending node* and is denoted by Ω. There is no ambiguity between this use of the symbol and its other use as stated above.

The angle DSP, denoted by ω, gives the direction of the perihelion point P from the line SD. These five geometrical relationships fix the size, shape and position of the orbit in space.

The sidereal period P and the epoch E, which give the time required by the planet to complete one revolution about the sun and the date when the planet was at some definite place in its orbit, such as at perihelion, complete the elements.

[1] The ascending node is indicated by the symbol ☊ and the descending node by ☋.

217. Orbit Computation.—The determination of the orbit of a planet or comet consists in the computation of the elements of its orbit. Such a computation is based on at least three observations of the right ascension and declination of the body as seen from the earth, the law of areas, the fact that the orbit lies in a plane passing through the sun and a knowledge of the relative positions of earth and sun at the times of the three observations. The relation of these various quantities are such that the elements of the orbit can be computed from them.

In the case of a newly discovered comet or asteroid it is of the greatest importance to obtain the three observations of position in order that a preliminary orbit may be calculated so that if bad weather prevents further observations for a time the object will not be lost. Except in very exceptional cases it is necessary to have the three observations made about a day apart in order to allow for changes in direction which are sufficient to permit a satisfactory calculation of the elements.

After receiving the three observations a good computer is usually able to calculate a preliminary set of elements in from 6 to 8 hours. The methods employed are either those developed by Gauss and Olbers about a century ago or an adaptation of Laplace's method brought to a high degree of perfection in the last few years by Leuschner of the University of California.

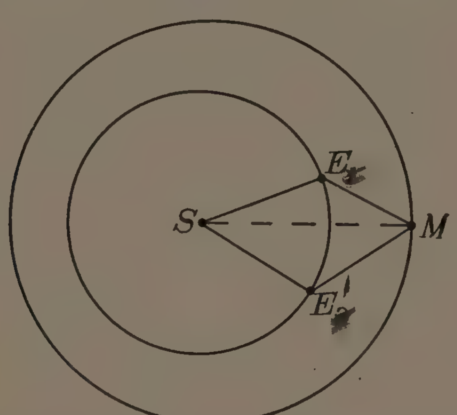


Fig. 115.—Method of determining a planet's distance from the sun in terms of the earth's distance from the sun.

218. Distance of a Planet in Terms of Earth's Distance.—If it is possible to make a series of observations of a planet at intervals of its sidereal period it is possible to determine its distance from the sun in terms of the earth's distance.

If we wish to determine the distance of Mars in this manner we observe its elongation from the sun SE_*M (Fig. 115) by means

of a meridian circle when Mars is at M and the earth at E_1. At the end of 687 days Mars will again be at M but the earth will be at E'_2. The elongation SE'_2M is again measured. In the quadrilateral $SE_1ME'_2$ we have measured the angles at E_1 and E'_2, the angle $E_1SE'_2$ will be the angle the earth passes over in 43 days (730 − 687) and SE_1, SE'_2 are radii of the earth's orbit. We can therefore solve the quadrilateral and determine SM in terms of SE_1. By similar observations of Mars at various points in its orbit its mean distance from the sun in terms of the earth's mean distance can be obtained.

219. The Zodiac.—A narrow belt of the sky 16° wide, extending along the ecliptic and bisected by it, is called the *zodiac*. Within this belt all planets known to the ancients as well as sun and moon are found.

The zodiac seems to have had an important place in the astronomy of all ancient civilizations. It was usually divided into 12 parts or constellations. These constellations, being of unequal extent, made unequal divisions, but this was changed by Hipparchus, the greatest of ancient astronomers of whom we have any record. In the second century B.C. he divided the zodiac into 12 sections of 30° each. These sections were called signs, corresponding to the constellations falling within their limits. The signs are still in use, although they have shifted from their constellations, owing to the precession of the equinoxes.

CHAPTER XII

THE TERRESTRIAL PLANETS AND THE ASTEROIDS

MERCURY

220. Elongation, Orbit, Period.—Mercury is the innermost of the planets. It is never seen very far from the sun, its greatest elongation being about 28°.

The planet's mean distance from the sun is 0.387 astronomical unit. Its orbit has both the greatest eccentricity, 0.206, and the greatest inclination to the plane of the ecliptic, 7° 0′, of any of the planets.

The *sidereal period* is very nearly 88 days and the *synodic period* 116 days.

221. Dimensions, Mass, Etc.—The diameter of Mercury is 4842 km (3009 miles). This makes it the smallest of the planets. Its volume is about one-eighteenth that of the earth.

The mass of Mercury is not easily determined, but a value of one-eighteenth that of the earth is probable. The density is therefore approximately that of the earth. The surface gravity[1] is about one-third that at the earth's surface.

222. Albedo.—The reflecting power of the planet is low, approximately 93 per cent of the sunlight falling on it being absorbed and only 7 per cent reflected. This reflecting power is called the *albedo*.[2]

The stellar magnitude (Sec. 351) varies from -1.9 downward.

223. Telescopic Appearance.—Mercury is difficult to observe, as it is so near the sun. When the sun is below the horizon the altitude of the planet is very small, even at greatest elongation, and the unsteadiness of the air at low altitudes makes observation unsatisfactory. If observed during the daytime the air is less steady than at night; the strong sunlight is also a drawback.

A few observers claim to have seen various markings on the planet's surface, but there is practically no agreement as to the

[1] The value of gravity at the planetary surfaces will be given in terms of that at the earth's surface throughout the book.

[2] The albedos of the planets and moon used in this book are those derived by Russell in his two papers in the *Astrophysical Journal*, vol. 43.

markings. Under ordinary conditions little or nothing can be seen.

Mercury shows phases like the moon. Figure 116 illustrates these phases and the relative diameters as the planet revolves about the sun.

224. Rotation.—The rotation period has not yet been determined. Some observers have thought they had evidence of a period somewhat like that of the earth, while others believe their observations can be satisfied only by a period practically coinciding with that of the period of revolution. Much remains to be done before the problem can be considered solved.

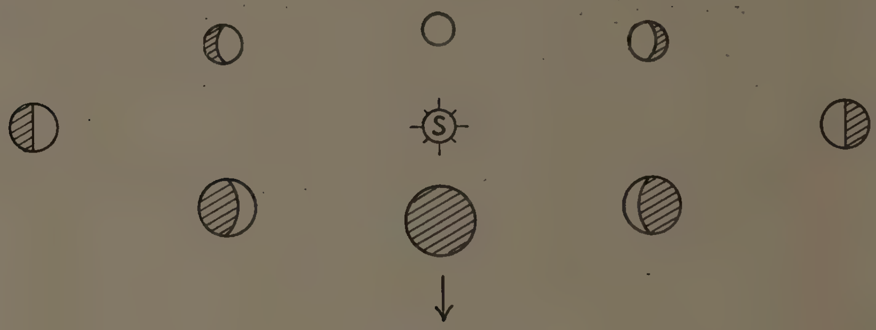


FIG. 116.—Phases of Mercury.

225. Transits.—Occasionally the planet passes directly between earth and sun so that it ~~can be~~ seen ~~projected~~ against the disc of the sun (Fig. 117). Such a phenomenon is called a *transit* across the sun. The last transit occurred on May 7, 1924, and the next two will occur on Nov. 8, 1927, and May 10, 1937.

During a transit the planet appears as a small black disc, about 12″ in diameter. This is much too small to be seen with the unaided eye. The transits are of no particular astronomical importance, nevertheless they are interesting phenomena to observe.

226. Motion of Perihelion.—A comparison of the positions of the perihelion point shows that this point is slowly moving eastward at the rate of 574″ per century. After allowing for the perturbations of the orbit by all the known planets, there remained about 42″ of this motion which could not be accounted for. The presence of unknown masses in the form of small planets or dispersed meteoric matter within the orbit of Mercury might account for this, but their presence in sufficient quantity has not been proved.

The Einstein theory of relativity achieved its first success by accounting for practically the entire amount. According to this theory, Newton's law of gravitation is not absolutely exact and requires a small correction. As a result of this the line of apsides of a planet should move forward in the same direction as the planet moves by a certain fraction of a revolution, $\frac{3v^2}{c^2}$, during each revolution (in this formula v represents the orbital velocity of the planet and c the velocity of light).

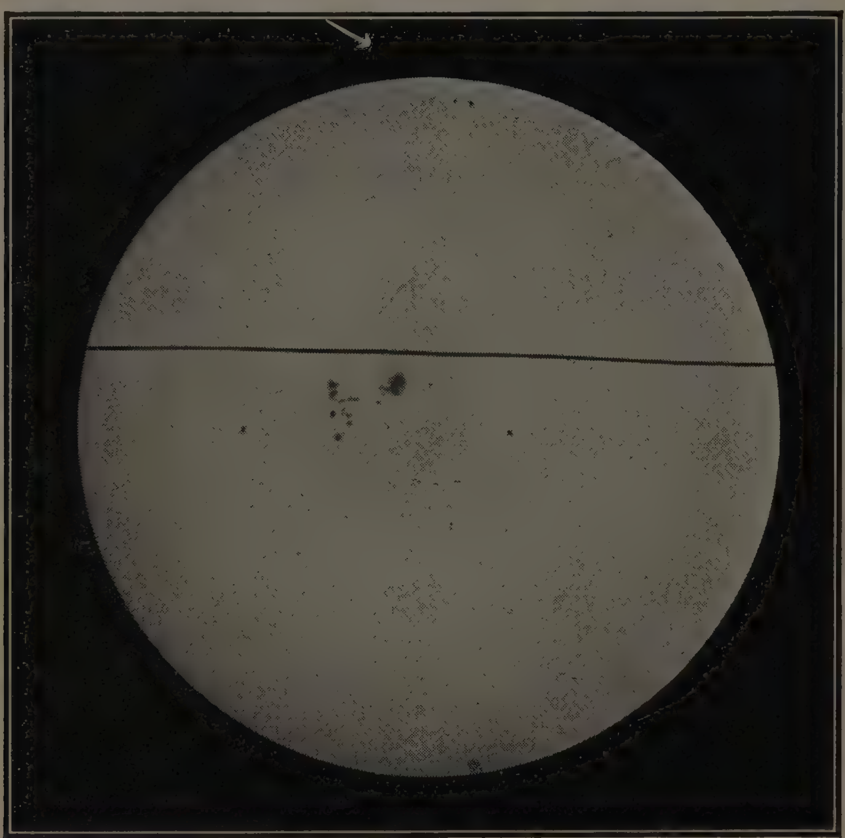


FIG. 117.—Transit of Mercury. The planet is the small black spot near the top as indicated by the arrow. (*Photographed by Barnard at the Yerkes Observatory.*)

Calculation by this formula gives 43″ per century as the amount of rotation of the line of apsides of Mercury's orbit in almost exact agreement with the 42″ required.

INTRAMERCURIAL PLANETS

227. The question as to whether there are any planets within the orbit of Mercury has often been raised. In a number of cases observers have reported such bodies, but from the evidence now available they seem to have been mistaken.

In one case the evidence seemed so good that the supposed planet was given the name Vulcan, and even the elements of its orbit computed, but as it has not been seen since we must look for some other explanation of the observations.

During total eclipses of the sun many efforts have been made to photograph possible intramercurial planets, but in 1902 Perrine, then at the Lick Observatory, wrote that if any such exist they must be less than 35 miles in diameter and have a brightness below magnitude 7.7.

VENUS

228. Orbit, Period, Etc.—Venus is the second planet in order from the sun. Its mean distance is 0.723. The orbit has an eccentricity of 0.007 and is inclined 3° 24′ to the plane of the ecliptic.

FIG. 118.—Phases of Venus showing the great range in apparent diameter as the planet passes from superior to inferior conjunction. (*Photographed by E. C. Slipher at the Lowell Observatory.*)

The *sidereal period* is nearly 225 days and the *synodic period* 584 days.

Its greatest elongation from the sun is about 46°.

229. Dimensions, Mass, Etc.—The diameter of Venus is 12,190 km (7575 miles), a value almost equal to that of the earth.

The mass of Venus, like that of Mercury, is somewhat uncertain, but it is about 0.82 that of the earth. Its mean density is

therefore about 5.2. The surface gravity is about five-sixths.

230. Albedo, Etc.—The albedo of the planet is quite high, 0.59, that of white paper being 0.70. Its stellar magnitude varies from -4.4 downward. This variation is due in part to its varying distance from the earth and in part to its phases. The great brightness of the planet permits it to be seen with the unaided eye in full daylight. When Venus is above the horizon during the night it will cause shadows.

231. Telescopic Appearance.—Venus shows phases like Mercury, but the apparent change in size is much greater, for at inferior conjunction the apparent diameter may be a little over 1′ while at superior conjunction it is only about 11″.

The usual telescopic appearance is that of a very bright white surface with occasional dimly seen shadings (Fig. 119). Some observers have reported spots of various kinds and others somewhat more definite markings. Such appearances, however, are usually evanescent and make it appear probable that the actual surface of the planet is not seen.

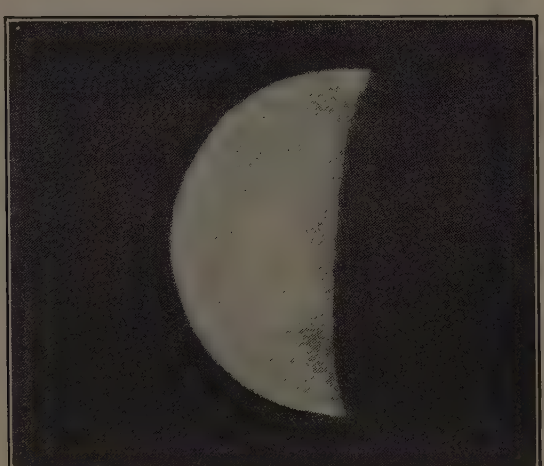


FIG. 119.—Drawing of Venus by Rordame. (*From Popular Astronomy.*)

232. Rotation.—Venus, like Mercury, may be said to have an unknown rotation period. Some observers, from the appearance of the illusive spots and shadings, have obtained periods of approximately 24 hours, while others bring evidence to show that the period of rotation is long, possibly equal to the sidereal period of revolution about the sun. At present it does not seem possible to decide between the two, but, in general, the evidence presented for a short period seems the more convincing. Two modern methods, the spectroscopic and the radiometric, will without

doubt ultimately settle the question, but especially good observing conditions lasting for a considerable time seem necessary.

233. Atmosphere.—The evidence in favor of at least a moderate atmosphere seems quite conclusive. At the times of inferior conjunction and transits a fine thread of light completely encircling the disc of the planet has often been seen. This can be explained either on the assumption that the light of the sun is sufficiently refracted by a fairly dense atmosphere to be bent around the edge of the planet's disc or that it is a twilight effect in an atmosphere of moderate density.

The extreme brightness of the disc and the lack of permanent markings afford strong evidence in favor of the view that the atmosphere of Venus is heavily cloud-laden. St. John and Nicholson of the Mt. Wilson Observatory have failed to obtain spectrographic evidence of water vapor, but this does not seem to be sufficient to disprove the cloud theory. The same observers also failed to find any evidence of oxygen, although their equipment was such that they should have detected both oxygen and water vapor had either been present to the extent of but 1 to 3 per cent of the amounts present in our own atmosphere. If we could be certain that the light reaching us from Venus had actually penetrated the greater portion of the planet's atmosphere before being reflected, then we could accept these results as proving the absence of appreciable quantities of these substances, but, since we do not know at what level most of the sunlight is reflected, the interpretation of the results must not be forced.

234. Physical Conditions.—Venus receives from the sun twice as much heat and light per unit area as the earth, but we do not know how much of this penetrates the atmosphere and actually reaches the surface of the planet. If the cloud envelope exists it is possible that the surface temperature is not much higher than on our globe, provided the rotation period is short. On the other hand, if rotation and revolution periods coincide, it would seem probable that the side turned toward the sun would have become intensely hot and any moisture present would have been borne away to the dark side long ago, deposited in the form of snow, and thus practically be locked up.

Observations by Coblentz and Lampland at the Lowell Observatory in 1924 show that the dark side of Venus radiates considerable heat. The most obvious inference is that the planet rotates on its axis so that the portion turned toward the sun

during the day retains enough heat to radiate this on the night side and that the rotation is sufficiently rapid so that the night side does not become very cold. We know nothing, however, about the location of the rotation axis and but little more about the period, so that further observations must be made before we can reason with any certainty concerning the physical conditions which obtain there.

235. Transits.—Transits of Venus across the solar disc are rare. The last two occurred on Dec. 9, 1874, and Dec. 6, 1882, and the next two will occur on June 8, 2004, and June 6, 2012. These transits have been used to determine the distance from earth to sun, but the results have not been satisfactory and better methods have been developed.

236. Satellites.—Venus has no known satellites. If any exist they must be very small. Several astronomers of the seventeenth and eighteenth centuries thought they saw a fairly large satellite, but the fact that it has not been seen in the last 150 years seems conclusive proof that they must have been mistaken.

MARS

237. Distance, Orbit, Period.—Mars is the outer one of the group of terrestrial planets. Its mean distance from the sun is 1.52 astronomical units.

The orbit has an eccentricity of 0.093, so that its distance from the sun varies 21×10^6 km (13×10^6 miles) each way from the mean. The orbit is inclined $1° 51'$ to the plane of the ecliptic.

The *sidereal period* is nearly 687 days and the *synodic period* nearly 780 days.

238. Dimensions, Mass, Etc.—The mean diameter of Mars is 6784 km (4216 miles), and there is a slight flattening at the poles. The volume is a little more than 0.151 and the surface about 0.28 that of the earth.

The mass is equal to 0.108 that of the earth, and the mean density is 4.0. The surface gravity is equal to 0.38, that is, an object weighing 100 pounds at the surface of the earth would weigh 38 pounds at the surface of Mars.

239. Albedo, Etc.—The mean albedo of the planet is about 0.15, but the determinations by various observers are not in the best agreement.

When Mars is very near the earth, as it was on Aug. 22, 1924, its stellar magnitude is -2.8, thus making its apparent brightness

greater than that of any other planet except Venus. This exceptionally high value was possible because Mars was near perihelion while the earth was near aphelion. Its apparent diameter was $25''.1$. The stellar magnitude near conjunction may be fainter than $+2.0$ and the apparent diameter only $3''.8$.

240. Rotation, Etc.—The rotation of the planet is easily seen when observed for an hour or more and the period is readily determined because of a number of well-marked surface features which have been under observation for centuries. By using old drawings, made by Huyghens over 250 years ago, in connection with modern observations the rotation period has been determined with great accuracy. It is found to be $24^h\ 37^m\ 22^s.7$.

The rotation axis is not perpendicular to the plane of the orbit, but is inclined about 25° to this perpendicular. In consequence, we can sometimes see about 25° beyond the pole which is turned toward us. The southern pole is the one thus situated when Mars is nearest the earth. As a result, the southern hemisphere is more easily studied than the northern.

241. Atmosphere.—The atmosphere around Mars appears to be comparatively thin. We know little about its composition. St. John and Nicholson of the Mt. Wilson Observatory find spectrographic evidence of very small amounts of oxygen and water vapor. The fact that clouds are seen very infrequently is additional evidence of a very limited amount of water vapor.

242. The Polar Caps.—The most conspicuous features on the surface of Mars are white areas around the poles. These vary in size with the seasons. When it is summer in the northern hemisphere the north polar cap shrinks rapidly, while the southern polar cap increases in size. When it is summer in the southern hemisphere the reverse process may be observed. The polar cap of the southern hemisphere has been studied in greater detail because it is turned towards us when the planet is nearest the earth. Such evidence as we have makes it likely that these white areas are composed of snow or heavy deposits of frost. If this is the case, they correspond to the snow fields of the earth which form in higher latitudes during the winters of the corresponding hemisphere and shrink toward the poles during the spring and summer.

243. Surface Temperature.—Until very recently we have had no knowledge whatever of the surface temperatures of Mars.

Various calculations had been made based on a variety of assumptions and the results varied as widely as the assumptions.

During the opposition of 1924, Coblentz and Lampland at the Lowell Observatory and Pettit and Nicholson at the Mt. Wilson Observatory investigated the problem by means of specially devised thermocouples used in connection with the large reflectors of the two observatories. The results of the Lowell observers indicate a temperature of −70°C. (−94°F.) at the north polar cap during the winter in the northern hemisphere, an average temperature of +14°C. (57°F.) at noon in equatorial regions, a temperature from 0° to 15°C. (32° to 59°F.) in the south polar regions as the south polar cap shrank during the summer time of the southern hemisphere, and a lower temperature of the edge just coming into the morning sunlight than of the edge passing into the night. The Mt. Wilson results, in general, support these values.

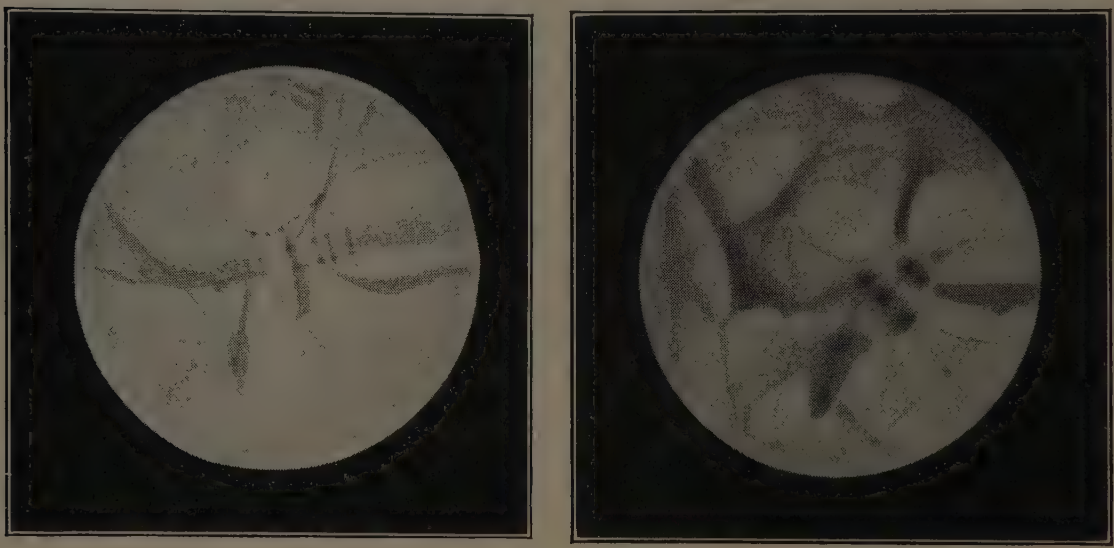
244. Surface Colors.—Aside from the polar caps the surface of Mars has two predominant colors, orange and bluish-green. Formerly, it was supposed that the orange regions were land and the bluish-green areas water, but modern observations have shown that there is much detail to be observed in the latter and that no large bodies of water exist. Some observers hold that the bluish-green areas are regions supporting some vegetation and the orange regions deserts. This does not seem improbable.

245. The Canals.—In 1877, Schiaparelli announced that he had observed many fine lines over the orange-colored surface of Mars, and in 1881 he further announced that in many cases these lines first appeared single and later double. He applied to them the Italian name "canali," which means channels, and which has been translated canals. Since that time many observers have seen these markings, those at the Lowell Observatory at Flagstaff, Ariz., paying especial attention to them and constructing charts of the planet showing many hundreds. Some of the more conspicuous ones have also been photographed at Flagstaff.

Many observers of Mars deny the existence of this network of fine straight lines, claiming that the markings are not only much broader individually but that there are considerable variations in width and direction. At the present time the majority of astronomers seem to favor the latter view.

An explanation of this marked difference of opinion may be as follows: There are on the surface of Mars many details which

cannot be seen individually but which the eye unconsciously integrates into lines and spots. If this is the case we would expect small telescopes to bring out the fine network while large telescopes, having a greater resolving power, would be able to bring out more detail and thus destroy the appearance of the network. As a matter of fact, and almost without exception, the observers who report seeing the fine canals use comparatively small telescopes, while those using the largest instruments in the world uniformly fail to see them, although they see much detail. Figure 120 is a reproduction of drawings by Hamilton and Trumpler showing the same regions on Mars. Hamilton used a 28-cm (11-inch) and Trumpler a 91-cm (36-inch) telescope.



A B

FIG. 120.—Drawings of Mars, showing the same surface features as seen by different observers: *A*. Drawn by Hamilton at Mandeville, Jamaica, Sept 8, 1924, using a 28-cm (11-inch) refractor. *B*. Drawn by Trumpler at the Lick Observatory, Sept. 11, 1924, using a 91-cm (36-inch) refractor (*From Popular Astronomy, March,* 1926.)

246. Life on Mars.—In the popular mind this question usually means "Is Mars inhabited by intelligent beings?" For us, however, it is necessary to distinguish carefully, first, between vegetable and animal life, and, second, between low forms of animal life and highly intelligent beings.

There seems to be no question about the existence of some sort of vegetation on Mars. Change in the color of the dark regions with change in season appears well established, but we have no way of determining whether this vegetation consists of the simple forms, such as might correspond to lichens and mosses on the earth, or of higher forms, such as trees.

If plant life exists it does not seem impossible that at least low forms of animal life also may be there, but no observations have been brought forward to establish this.

The question of intelligent life on Mars hinges almost exclusively on the interpretation of the canals. The argument is as follows: Nowhere in nature do we find long straight lines. Our experience on the earth is that only man produces projects, such as canals or railways, which follow essentially straight lines for long distances. The network of fine straight lines therefore clearly implies an artificial and not a natural system of markings. Hence there are intelligent beings on our neighboring planet who are responsible for these markings. Water seems scarce on Mars, so these intelligent beings constructed a great system of water courses leading from the warmer equatorial regions toward the poles in order to carry the water from the melting polar caps to regions where crops may be grown. The markings seen and called canals are not the artificial water courses themselves but the irrigated regions of growing crops along their sides.

It will be seen that the argument depends essentially on the straightness of the canals. Since, however, as stated above, the world's keenest observers using the most powerful telescopes fail to see this network of fine straight markings, although they see a great amount of what we may term "natural detail," the argument for the existence of intelligent Martians capable of carrying out great engineering works is seen to rest on very insecure foundations.

Professor W. H. Pickering has made many observations which indicate a shifting of the positions of many of the canals, and thinks that they are strips of vegetation which shift in position with changes in the precipitation as the prevailing winds may affect the latter.

247. The Satellites of Mars.—Mars has two satellites which were discovered by Hall at Washington in 1877. They are both small and the inner one is especially difficult to see. They are too small to show appreciable diameters, but, on the assumption that their albedo is the same as that of Mars, their diameters are about 9 km (6 miles) according to Pickering; the inner 58 km (36 miles) and the outer one 16 km (10 miles) according to Lowell and Douglass.

The orbits of both are sensibly circular, the smaller with a radius of 9300 km (5800 miles) and the larger with a radius of 23,500

km (14,600 miles). Both orbits lie sensibly in the plane of the planet's equator. Their periods of revolution are $7^h\ 39^m$ and $30^h\ 18^m$ respectively.

The inner satellite is the only one known which goes around its primary in a period shorter than the rotation period of the latter. Because of the rapid revolution it rises in the west and sets in the east, while the other rises and sets in the usual way, although it requires about 132 hours between successive risings or settings.

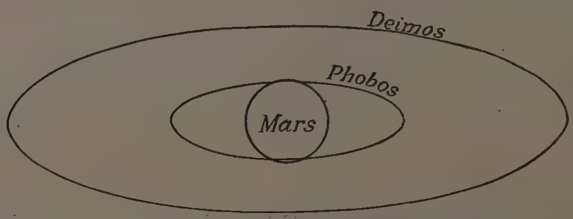


FIG. 121.—The orbits of the satellites of Mars.

The name of the outer satellite is Deimos and of the inner one Phobos.

THE ASTEROIDS

248. Early Discoveries.—The possibility of the existence of a planet between Mars and Jupiter had been recognized as early as the time of Kepler in the seventeenth century. When Bode's law was announced over a century later the possibility became a probability and led to an organization in Germany for the purpose of looking for the unknown planet. Apparently, however, no great efforts were expended on the search and the actual discovery of the first asteroid fell to Piazzi in Palermo, Italy.

While observing a certain region of the sky on the night of Jan. 1, 1801, he came across a telescopic star which had moved appreciably by the following night. He followed it with care for 6 weeks and was then forced by illness to abandon the work.

News of the discovery reached Germany in March, but the planet, to which Piazzi had given the name Ceres, was then too near the sun to be observed, and it was necessary to wait until fall before the search could be continued. The question at that time, however, was where to look for it. During the summer the mathematician Gauss attacked the problem and devised his famous method of determining orbits. Applying the method to Piazzi's observations he predicted where the planet might be found and Ceres was rediscovered at the end of the year.

A few months later Olbers discovered a second asteroid which he named Pallas; Harding discovered Juno in 1804 and Olbers found a fourth, Vesta, in 1807. For nearly 40 years these four were the only ones known and it was not until 1845 that Hencke, an amateur astronomer, found the fifth. Since 1847 no year has passed without new discoveries and over a thousand are now (1925) known.

249. Methods of Search.—For many years the search was carried on visually by making charts of the faint stars near the

FIG. 122.—Trail of asteroid Egeria. (*Photographed by Parkhurst at the Yerkes Observatory.*)

ecliptic and then comparing these with the sky. If a star was found which was not on the chart it was carefully observed, and, if found to be in motion, sufficient observations were obtained so that an orbit could be computed.

The modern method, inaugurated by Wolf of Heidelberg, consists in photographing regions near the ecliptic with special cameras of large aperture and field. The camera is mounted so that it is moved by clockwork to follow the stars across the sky. When exposures of some duration are made, the stars will give round images, but if an asteroid is in the field its motion will produce a short line or trail (Fig. 122) which betrays its presence.

250. Designation.—The asteroids were originally named but when their number mounted into the hundreds it became difficult to find suitable names. Later each asteroid on discovery was given a provisional designation, such as 1920 HZ, which shows the year of discovery and the order. The next one in the same year would be 1920 JA, the next 1920 JB, etc., the letter I being omitted. When sufficient observations have been obtained to compute an accurate orbit the asteroid is given a special number enclosed in parentheses if it proves to be a new one. Thus 1920 HZ became (944).

Beginning with Jan. 1, 1925, a new method of designation has come into use. The letters of the alphabet are divided according to the months, alloting two letters to each month but omitting I and Z. Following these letters the letters are used a second time from A to Z if necessary (excepting I) as follows:

The first asteroid of the year, if discovered in the first 15 days of January, 1925, is designated 1925 AA, the second 1925 AB, etc. Those discovered from the 16th of January onward would be 1925 BA, BB, etc. Similarly the February asteroids would be 1925 CA, CB, etc. and 1925 DA, DB, etc. For 1926 the letters would be used again as in the preceding year, the only change made being in the number of the year.

The discoverer is still at liberty to assign a name but frequently the right is not used.

251. Size.—Most of the asteroids have diameters less than 100 km but a few are large enough to be measured. Thus Barnard found values of 768, 489, 385 and 193 km (477, 304, 239 and 120 miles) for Ceres, Pallas, Vesta and Juno respectively by using powers of 1000 to 1700 with the Lick 36-inch and Yerkes 40-inch refractors. Most of them, however, are too small to show a measurable disc and some are without doubt less than 10 km in diameter. Thus, judging from its brightness, (719) Albert probably has a diameter of not over 4 or 5 km.

252. Orbits.—Almost all the asteroids have mean distances from the sun lying between the values of 2.0 and 3.5 A.U., but the range is from 1.46 for Eros to 5.72 for (944), so that the entire region from slightly within the orbit of Mars to slightly beyond the orbit of Jupiter is covered by the asteroids. Exceptional cases may still be discovered which will increase the width of the asteroid belt.

The eccentricities vary from 0.00 to 0.653, but most of the values are below 0.30.

The inclinations to the plane of the ecliptic vary from 0° to 43°, but most of them are less than 16°.

The period of the average asteroid is about 4.5 years, but Eros revolves about the sun in 1.8 years, while (944) requires over 13 years.

253. Eros (433).—This asteroid was discovered photographically by Witt of Berlin in 1898. The computation of its orbit showed it to be an exceptional one. Its mean distance from the sun is 1.46 and its eccentricity of 0.22 brings it at times very close (about 22,000,000 km) to the earth. In 1900 it came within about 47,000,000 kilometers and the favorable opportunity was utilized to organize an international campaign for the determination of the distance between earth and sun, with the result that we now know this value more exactly than ever before (see Sec. 149). In 1931 it will come much nearer than in 1900 and preparations are being made to utilize the favorable opportunity.

254. The Trojan Group.—Six members of this group are known at present. All have mean distances from the sun differing but little from that of Jupiter. It has been shown that if three bodies, essentially at equal distances, move about their common center of gravity in a plane, they will maintain their relative distances at the vertices of an equilateral triangle. These six asteroids, each in connection with Jupiter and the sun, very nearly fulfil these conditions.

255. Perturbations by Jupiter and Saturn.—All the asteroids are influenced to a marked degree by Jupiter and perturbations by this planet cause great changes in the orbits. Saturn also has some influence, but much less than Jupiter. On this account an asteroid orbit, however carefully determined, will not suffice to predict its future position for any length of time without the calculation of the perturbations by Jupiter and Saturn. This is a rather long and tedious process. Watson, one of the chief American discoverers of asteroids in the last century, realized that the 22 bodies discovered by him might be lost[1] on account of the changes in the orbits and at his death left a sum of money to the National Academy of Sciences, Washington, D. C., in order to have tables of the perturbations calculated so that it would be a simple matter to determine and apply the corrections

[1] In fact, one of the 22, Aethra (132), was lost within a few weeks after discovery in 1873 and not recovered until found by chance in 1922.

to the ever-changing orbits. This work was put into the hands of Prof. A. O. Leuschner of the University of California and is now practically completed.

256. Variation in Brightness.—All of the asteroids vary in apparent brightness, depending on their distance from sun and earth, but in a number of cases they also undergo other variations in brightness which seem to indicate possible rotation effects by presenting light and dark sides alternately toward the earth. It is possible, too, that some of the smaller asteroids are not even approximately spherical, but more or less angular. If this is the case we would expect variations in brightness depending upon whether a more or less flat side or an angle is turned toward the earth.

257. The Masses.—We have little knowledge of the masses of the individual asteroids, but it is probable that the combined mass of all those known barely exceeds 0.001 that of the earth.

258. Origin.—When the first asteroids were discovered Olbers suggested that they might be the fragments of a disrupted planet. This idea is now generally given up. It appears more probable that they are the material from which a planet might have been formed had not the presence of Jupiter prevented it by the disturbances induced in the motions of the small masses concerned. The meaning of this statement will be clearer when the theories of the origin of the solar system are considered in Chap. XIX.

CHAPTER XIII

THE MAJOR PLANETS

JUPITER

259. Distance, Orbit, Etc.—Jupiter is one of the brightest of the planets. Its mean distance from the sun is 5.20 astronomical units (778×10^6 km, or 483×10^6 miles). The orbit has an eccentricity of 0.048, which allows a variation of over 37×10^6 km (23×10^6 miles) each way from the mean distance. The orbit is inclined 1° 18′ to the plane of the ecliptic.

The *sidereal period* is 11.86 years and the *synodic period* 399 days.

260. Dimensions, Mass, Etc.—The mean diameter of Jupiter is 139,600 km (86,700 miles), but on account of its rapid rotation it is markedly flattened at the poles. The polar diameter is 133,200 km (82,750 miles) and the equatorial diameter 142,700 km (88,700 miles).

The volume of the planet is approximately 1300 times that of the earth, while its mass is only 318 times the earth's mass. Its mean density is, therefore, only one-fourth that of the earth or 1.4 on the water standard.

Its surface gravity is about 2.5.

261. Albedo, Etc.—The mean albedo of Jupiter is 0.56, although the different parts of the surface differ considerably from one another. At mean opposition its brightness equals that of a star of magnitude -2.3. This changes to about magnitude -1.5 near conjunction.

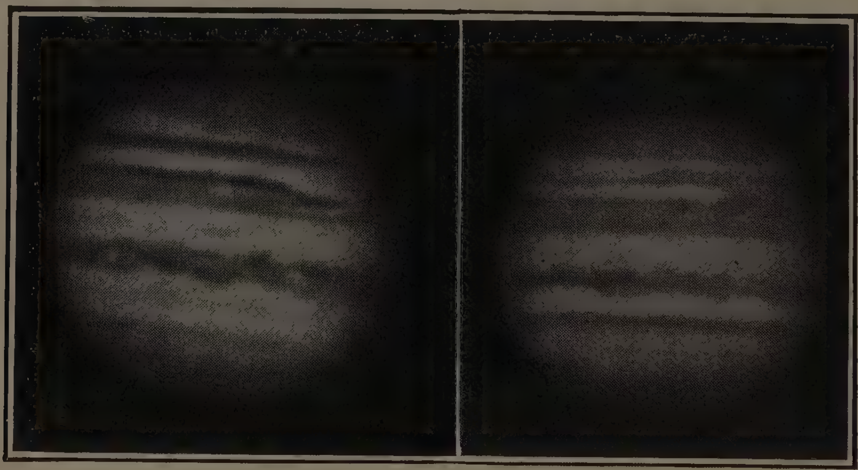
In brightness the planet is generally exceeded only by Venus, but Mars will outshine it for a few weeks during a very close approach.

262. Telescopic Appearance.—When seen with a small telescope of 3- or 4-inch aperture and a magnifying power of about 100 a number of approximately parallel bands of different widths may be noted. These bands are of a dull reddish color as seen against the remainder of the surface, which is of a white or yellowish tinge. The use of a larger telescope and a magnifica-

tion of 200 or more will show much detail in these bands (or belts), and this finer structure, at times, will be found to undergo considerable variation from one night to the next.

Fig. 123.—Drawing of Jupiter, Oct. 26, 1916, by Latimer J. Wilson, showing bright and dark spots. (*From Popular Astronomy.*)

Occasionally small spots are seen which may be either dark or bright, but, for the most part, these spots are comparatively short-lived phenomena. In 1878, however, a large oval spot



A *B*

Fig. 124.—Jupiter as photographed by E. C. Slipher at the Lowell Observatory. *A*, 1915; *B*, 1917.

having a width of about 14,000 km (8700 miles) and a length of about 40,000 km (25,000 miles) became a very conspicuous object on the planet's surface. It became known as the "Great Red Spot" on account of its size and color. As the years passed

the Great Red Spot gradually lost most of its color, but its outline is still partially visible.

The brightness of the surface falls off considerably near the edge—an indication of atmospheric absorption. This phenomenon is particularly marked on photographs of the planet's surface.

263. Rotation Period.—Observation of well-marked spots on the surface shows that Jupiter is in rapid rotation. The various determinations are not wholly in agreement and there is evidence that, while the rotation period from spots at the equator is 9^h $50^m.5$, the period given by other spots in higher latitudes is about $9^h\,55^m$. Whether there is a regular progression from the one value to the other with increasing distance from the equator is not yet certain.

Spectrographic rotation values agree with those determined visually.

264. Physical Conditions on Jupiter.—Since the planet is over five times as far from the sun as the earth, the amount of heat and light falling on equal areas of the two is in the ratio 1:27. We can therefore feel sure that if Jupiter is dependent upon the sun for heat its temperature is low.

The changing belts and the appearance and disappearance of spots seem almost conclusive against our actually seeing a solid surface. The simplest explanation is that we see the upper side of a cloud-laden atmosphere, but this does not account for the semi-permanent belts or for the long-enduring migrating Great Red Spot. Possibly there is a partially solid surface underneath a cloudy envelope and the character of the surface determines the location of the belts, while changes at the surface cause violent atmospheric disturbances which, in turn, cause the changes seen through the telescope.

If such a partially solid surface exists it must be quite different from the earth's crust. The low mean density (1.4) would lead us to suppose the surface density less than that of water. The violent disturbances seen through the telescope have led many to assume that Jupiter possesses considerable internal heat, but there is little evidence to support this conjecture.

265. The Satellite System.—Jupiter has nine known satellites. The four brightest were the first new bodies discovered by the telescope, as they are bright enough to be seen easily in a good field-glass. They were discovered independently by Galileo and by Simon Marius in January, 1610. The diameters of these

satellites, in the order of their distances from their primary, are 3950, 3290, 5730 and 5390 km, according to Barnard. Their periods of revolution are $1^d\ 18^h$, $3^d\ 13^h$, $7^d\ 4^h$ and $16^d\ 18^h$ respectively. Their orbits are practically in the plane of Jupiter's equator and almost circular. There is some evidence that one or two of them rotate at such a rate that they present the same face toward the planet, but further observations are required to confirm this.

The fifth satellite was discovered by Barnard at the Lick Observatory in 1892. It is probably about 160 km (100 miles) in diameter, its period of revolution is 12 hours and it is only 182,000 km (113,000 miles) from Jupiter's center.

The sixth and seventh satellites were discovered photographically by Perrine at the Lick Observatory in 1904 and 1905; the eighth similarly by Melotte at Greenwich in 1908 and the ninth by Nicholson at the Lick Observatory in 1914. The periods of revolution of the last four satellites are 266, 276, 739 and 750 days respectively. They are all small, ranging from about 150 to 25 km in diameter, according to an estimate of Nicholson.

The first seven move about Jupiter in the same direction as the planet moves about the sun (west to east), but the last two move in the opposite direction in orbits inclined 55° and 68° respectively to the plane of the planet's equator.

266. Satellite Transits and Eclipses.—In their movements about Jupiter the first three of the brighter satellites pass regularly, and the fourth frequently, between that planet and the earth, and can be noted as small bright points at such times, particularly when there is a dark belt of the planet for a background. The shadows of the satellites appear as small black spots on Jupiter's surface.

When one of these satellites is on the farther side of Jupiter it also passes into Jupiter's shadow and disappears from view. The eclipse is not instantaneous but requires some seconds. It is an interesting observation and easily made when the planet is not too near opposition to prevent following the satellite into the shadow.

267. Jupiter's Satellites and the Velocity of Light.—After the four brighter satellites had been observed, so that their mean periods were known with some degree of accuracy, it was found that if eclipses of the satellites were predicted by starting from observed times of eclipse near opposition the eclipses of the four

occurred systematically later and later, until near conjunction they were many minutes behind the predicted times. After conjunction the discrepancy decreased correspondingly until near opposition the eclipses again occurred on time.

Roemer, a Danish astronomer stationed at Paris at the time, was engaged in the problem of improving the tables of the satellites used to predict the eclipses. He found a maximum discrepancy of 22 minutes between the observed and computed times and suggested the true explanation, namely, that light does not pass instantaneously from one point of space to another but requires 22 minutes[1] to cross the earth's orbit. This was in 1676. His explanation was not generally accepted at the time but Bradley's discovery of the aberration of light in 1726 proved Roemer's theory to be correct.

FIG. 125.—Phenomena of Jupiter's satellites and the velocity of light.

An inspection of Fig. 125 shows that if E_1 and J_1 represent the positions of the earth and Jupiter at a certain time, and E_2 and J_2 the corresponding positions 6 months later, the distance E_2J_2 is practically equal to $E_1J_1 + E_2E_1$. Hence a signal, such as a satellite eclipse or transit, would reach E_2 later than E_1, the difference being the time required for light to travel across the earth's orbit.

SATURN

268. Distance, Orbit, Period.—Saturn was the outermost planet known to astronomers until late in the eighteenth century when Uranus was discovered. Its mean distance from the sun is 9.54 astronomical units.

The orbit has an eccentricity of 0.056 and is inclined 2° 29′ to the plane of the ecliptic.

The *sidereal period* is 29.458 years and the *synodic period* is 378 days.

[1] The modern value is 16.6 minutes

269. Dimensions, Mass, Etc.—Saturn has a marked oblateness, its polar diameter being 112,300 km (69,800 miles) and the equatorial diameter 123,100 km (76,500 miles). The mean diameter is 116,600 km (72,500 miles). Its volume is therefore about 760 times that of the earth.

The mass of the planet is only 95 times the earth's mass. Its mean density is the lowest of all the planets, being only 0.7 that of water. The surface gravity is about equal to that of the earth.

270. Albedo.—The mean albedo of the planet is 0.63, but its great distance from the sun makes its actual surface brightness comparatively low. Its stellar magnitude varies from about 0 to 1.5, depending upon its distance from the earth and upon the angle which the rings make with the line of sight.

271. Rotation.—The period of rotation is difficult to determine, as few spots are ever seen on its surface. The value obtained by Hall of Washington, $10^{h}\ 14^{m}$, is probably not far from the correct value, but it is possible that, like Jupiter, the planet has no single period.

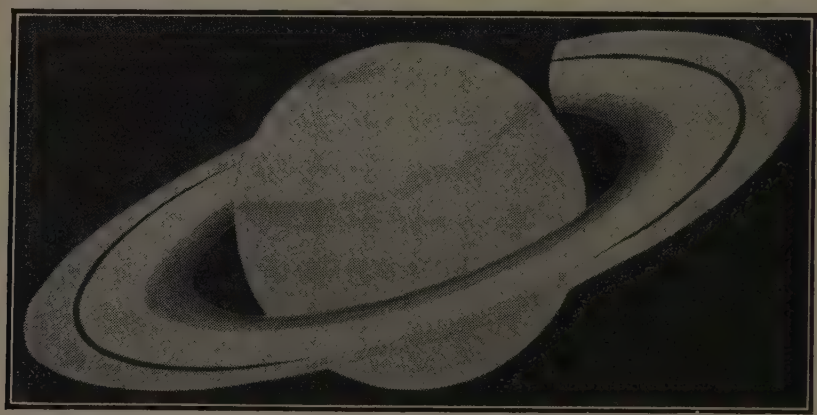


Fig. 126.—Drawing of Saturn. (*By Keeler.*)

The rapid rotation causes a marked bulging at the equator which is easily seen through the telescope.

The plane of Saturn's equator is inclined 28° to the plane of its orbit, so that it must have marked seasonal changes, at least in so far as sunlight is concerned.

272. Telescopic Appearance.—When seen through the telescope the planet shows an almost uniform surface of a slightly yellowish tint with a few poorly defined belts parallel to the equator. There is a decided falling off in brightness near the edge of the disc, which indicates considerable atmospheric absorption.

At irregular intervals, usually of some years' duration, one or more spots may appear on the surface. Usually these spots are white, but dark ones are not unknown. They are comparatively short-lived phenomena, lasting only a few months at most, and afford the only satisfactory means of determining the period of rotation except the spectrographic method.

273. Physical Condition.—There is great difficulty in coming to any conclusion regarding the physical conditions obtaining on Saturn. Its extremely low mean density seems to preclude much solid or liquid matter as we know it. If there is such a solid or liquid core it must be enveloped by a very extensive atmosphere, probably filled with clouds, which hide the interior.

The white spots which sometimes are seen have the appearance of an eruption of some substance from beneath the level we ordinarily see, but we have no knowledge of its temperature. The spots may be merely especially bright clouds, for sometimes, as in 1876 to 1877, they gradually lengthen in a direction parallel to the equator and fade out as if mixed with other atmospheric constituents.

It has been thought that Saturn may have considerable internal heat, but there is no definite evidence for this assumption.

274. The Rings.—The most interesting and impressive thing about the planet is its system of rings. There are three of these, usually spoken of as the outer, inner and crêpe or dusky rings. The outer ring has an outer diameter of 277,400 km (172,400 miles) and a width of 17,500 km (10,900 miles); the inner ring has an outer diameter of 235,000 km (146,000 miles) and a width of 28,800 km (17,900 miles). There is a gap of 3600 km (2300 miles) between the two rings, which is known as the Cassini division. The dusky or crêpe ring seems to touch the inner ring and extends inwards 17,700 km (11,000 miles). Between the inner edge of the dusky ring and the planet there is a gap of about 9400 km (5900 miles). The thickness of the rings is not easy to determine, but it is probable that they are not over 100 km in thickness.

The inner ring is much brighter than the outer, and the dusky ring must be looked for with some care in order to be seen at all.

For many years the constitution of the rings was in doubt, but the spectroscopic work of Keeler at the Allegheny Observatory in 1895 showed that the period of revolution about Saturn increased progressively with increasing distance from the planet.

They could, therefore, not be solid. The most probable constitution is that of myriads of small satellites of various sizes, each pursuing its own orbit about Saturn, but so small that at the earth's distance the individual constituents cannot be seen. There is evidence that the total mass of the ring is very small, probably less than 0.00001 that of Saturn. The rings may therefore be merely clouds of fine material like dust or grains of sand, for all of the rings, even the brightest, are sufficiently transparent to allow stars of moderate brightness to be seen through them.

The plane of the rings coincides with the plane of the equator of Saturn, which is inclined 28° to the plane of the ecliptic. When the earth is in the plane of the rings these disappear from view for all except the largest telescopes. Such disappearances occur about every 15 years. The last time was in 1921. As the rings gradually shift their plane more and more from the direction toward the earth they become visible again and afford a wonderful spectacle to astronomer and layman alike.

275. Satellites.—Saturn has nine known satellites. Huyghens discovered the first in 1655; Cassini the next four in the period

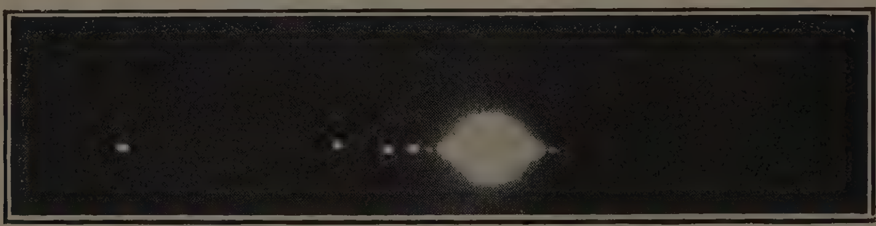


Fig. 127.—Six satellites of Saturn photographed by E. C. Slipher at the Lowell Observatory March 2, 1921. From left to right the satellites are Titan, Rhea, Dione, Tethys, Mimas and Enceladus.

from 1671 to 1684; Sir William Herschel the next two in 1789; Bond of Harvard the eighth in 1848; and W. H. Pickering of Harvard the last in 1899. In 1904, Pickering also found an object on some photographic plates which appeared to be moving about Saturn and it was announced as a tenth satellite. It was followed for a few months and then lost, and has not been recovered since. In general, the order of discovery of the satellites is their order of brightness. The innermost satellite, Mimas, moves about Saturn at a distance of about 187,000 km (117,000 miles) from the planet's center in a period of approximately 23^h, while the outermost, Phoebe, is at a distance of nearly 13,000,000 km (7,300,000 miles) and requires 550 days to complete a single circuit.

With the exception of the two outer satellites, Japetus and Phoebe, their orbits lie approximately in the plane of the ring. All of them move about Saturn from west to east except Phoebe, which moves in the opposite direction.

A number of the satellites show some variation in brightness. This is particularly true of Japetus, which has the remarkable property of being regularly brighter when west of Saturn than when east of it. The usual explanation of this phenomenon is that Japetus, like the moon, always turns the same face toward its primary and therefore we see opposite sides of the satellite when it is on opposite sides of Saturn. If this is the case, and if these sides do not have the same mean albedo, then such a variation in its light is a necessary consequence.

URANUS

276. Discovery.—In the late winter of 1781, while William Herschel was observing with a 6¼-inch reflector of 7-foot focus of his own make, a small round object came into the field of view of his telescope. His practiced eye immediately noted that it was different from an ordinary star and he determined to watch it with care. It was soon found to be in motion with respect to the stars in the field and he announced that he had discovered a new comet. It was followed with care but every effort to calculate an orbit on the assumption of its being a comet near the earth and sun failed. After some months it proved to be in reality a new planet, twice as far from the sun as Saturn.

277. Distance, Orbit, Period.—Uranus, as the new planet came to be named, has a mean distance of 19.19 astronomical units from the sun. The eccentricity of the orbit is 0.047 and its plane is inclined $0° 46'$ to the plane of the ecliptic. This is the smallest inclination of any planet orbit.

Its *sidereal period* is 84.0 years and its *synodic period* 369.7 days.

278. Diameter, Etc.—The diameter is not easily determined for two reasons: (1) its small apparent diameter, about $3''.8$, and (2) its somewhat indefinite outline. For these reasons the measures of various observers differ considerably. A value of 49,700 km (30,900 miles) is the mean of several determinations. This makes the volume 59.3 times that of the earth.

279. Mass, Density, Etc.—The mass of Uranus is 14.6 times the earth's mass and its density about 1.3 times that of water. The surface gravity is a little over 0.9.

280. Rotation.—Lack of definite surface markings has prevented a determination of the rotation period by the usual method, but V. M. Slipher has obtained a value of $10^h.8$ by the spectroscopic method. The rotation is retrograde and the plane of the equator makes an angle of 82° with the plane of the ecliptic.

281. Albedo, Etc.—The albedo is 0.63, the same as for Saturn. Under favorable conditions the planet can be seen with the unaided eye as a star of the sixth magnitude.

282. Satellites.—Uranus has four satellites. Two were discovered by Sir William Herschel in 1787 and the other two by Lassell in 1851. Their periods range from 2.5 to 13.5 days. Their orbits make an angle of 82° with the plane of the ecliptic and the direction of revolution is retrograde. They revolve in the plane of the planet's equator and in the same direction as the planet rotates if Slipher's spectrographic results are accepted.

NEPTUNE

283. Discovery.—In 1821, Bouvard of Paris published tables of the motions of a number of planets, including Uranus. In preparing the latter he had found great difficulty in making an orbit calculated on the basis of positions obtained in the years after 1800 agree with one calculated from observations taken in the years immediately following discovery. He finally disregarded the older observations entirely and based his tables on the newer observations. In a few years, however, the positions calculated from the tables disagreed with the observed positions of the planet and by 1844 the discrepancy amounted to 2′ of arc. Since all the other known planets agreed in their motions with those calculated for them, the discrepancy in the case of Uranus aroused much discussion.

In 1845, Leverrier, then a young man, attacked the problem. He checked Bouvard's calculations and found them essentially correct. Thereupon he felt that the only satisfactory explanation of the trouble lay in the presence of a planet somewhere beyond Uranus which was disturbing its motion. By the middle of 1846 he had finished his calculations. In September he wrote to Galle at Berlin and requested the latter to look for a new planet in a certain region of the sky for which some new star charts had just been prepared in Germany but of which Leverrier apparently had not as yet obtained copies. On the twenty-third of September Galle started the search and in less than an hour he found an

object which was not on the chart. By the next night it had moved appreciably and the new planet, subsequently named Neptune, was discovered within 1° of the predicted place. This discovery ranks among the greatest achievements of mathematical astronomy.

In 1843, J. C. Adams, at that time a student at the University of Cambridge (England), had also attacked the Uranus problem. Two years later he had finished his calculations on the assumption that an undiscovered planet was the cause of the discrepancy in the motion of Uranus and communicated his results to Airy, the Astronomer Royal at Greenwich. Airy, however, did nothing until the next year when the results of Leverrier's calculations were published. The agreement between the two calculations was so striking that he felt called upon to make an effort to find the predicted planet by requesting Challis of Cambridge to take up the matter with the University telescope. The plan consisted in getting the positions of all the faint stars in a considerable region around the predicted place and then reobserving them to see if any had moved. Challis had gone over the list of stars a second time when word was received of the discovery at Berlin. It was then found that Challis had actually observed the new planet twice, and, had he made the necessary comparisons immediately, he would have had the honor of discovery. While Adams' work was therefore barren of results, he must nevertheless be given full credit, along with Leverrier, of having determined independently the data by means of which the actual discovery could be made.

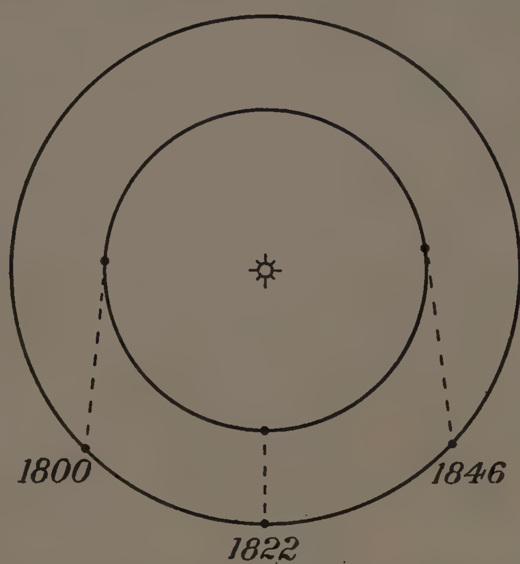


FIG. 128.—Relative positions of Uranus and Neptune at various times. It is evident that the perturbations of Uranus by Neptune before 1822 would be different from those after 1822.

284. Distance, Orbit, Period.—Neptune's mean distance from the sun is 30.07 astronomical units. The eccentricity of the orbit is 0.0086 and its inclination to the ecliptic is 1° 47′.

The *sidereal period* of the planet is 164.79 years and the *synodic period* 367.5 days.

285. Diameter, Etc.—As in the case of Uranus, the diameter of Neptune is not easily determined. Barnard's measures give the value 53,000 km (33,000 miles). Its volume is accordingly 72 times that of the earth.

286. Mass, Density, Etc.—The mass of Neptune is 17 times the earth's mass and its mean density about 1.2 times that of water. The surface gravity is about 0.9.

287. Rotation.—Definite surface markings cannot be seen and no reliable rotation period has been determined. The spectrographic method also has yielded no results.

In 1922 and 1923, Oepik and Livländer of Tartu, Russia, obtained a long series of photographic observations of the brightness of Neptune. From these they found a variation in brightness of about 0.14 magnitude with a period of about $7^h.8$. The simplest explanation is that Neptune has a rotation period of this value, different surface markings being presented on the visible hemisphere because of its rotation. Further investigation is necessary, however, before this explanation can be accepted without reservation.

288. Albedo, Etc.—The albedo of Neptune is 0.73. Its average stellar magnitude is 8. It is therefore never visible to the naked eye.

289. Telescopic Appearance.—In a telescope Neptune appears as a small round disc of $2''.5$ diameter, without definite markings and of a faint bluish color. Under ordinary conditions of seeing the edge is not sharply defined.

290. Satellite.—Neptune has one known satellite which was discovered by Lassell within a few months after the planet itself had been found. The satellite makes one revolution around its primary in $5^d\ 21^h$ in an orbit inclined 37° to the plane of the ecliptic. The motion in the orbit is retrograde, that is, from east to west. The distance of Neptune makes it impossible to measure the diameter of the satellite but, on the assumption that its albedo is the same as that of the planet, Pickering obtained a diameter of 3600 km (2240 miles).

291. Transneptunian Planets.—We have no knowledge of the existence of any planets beyond Neptune. A number of astronomers have advanced reasons why they believe one or more to

exist, but up to the present time none has been discovered. There seems to be no particular reason why Neptune should be the outermost of the planets and it is possible that others may yet be found.

THE ZODIACAL LIGHT

292. In northern latitudes from about the middle of January to the middle of March there may be seen in the west after darkness falls a faint pyramid of light from 20° to 30° wide at the base and rising from 40° to 50° above the horizon. The axis of the light lies nearly in the ecliptic, which at this time of year is most nearly perpendicular to the western horizon in the early evening. The same phenomenon may be seen in the east before dawn during August, September and October when the ecliptic is most nearly perpendicular to the eastern horizon before dawn. The light is strongest near the horizon and becomes fainter with increasing altitude.

In regions where the sky is especially free from dust and haze this light can be seen joining a faint band about 10° wide extending from the usually seen pyramid entirely across the sky. At a point opposite the sun the band increases considerably in brightness and width. This brighter region is known as the *counterglow* or *gegenschein.* Whether the gegenschein is really a part of the zodiacal light or not has not been fully determined, but the prevailing opinion favors the connection.

At certain latitudes, where the sun is just far enough below the northern horizon in the summer at midnight to eliminate twilight effects, the light can be traced along the northern horizon to a distance of 46° from the sun in a direction perpendicular to the ecliptic.

The simplest explanation of the phenomenon is that there is a certain amount of dispersed matter, possibly dust and larger fragments, in a lens-shaped region surrounding the sun. Its greatest extent is near the plane of the ecliptic; it extends beyond the earth's orbit and its density diminishes with increasing distance from the sun. This material would reflect some of the sunlight falling on it and present the general appearance described above. This explanation is known as the meteoric theory of the Zodiacal Light. It is confirmed by the observations of Wright in 1874, who found from 15 to 20 per cent of the light polarized, and by the spectrographic observations of Fath in 1909, who found the spectrum to resemble the spectrum of sunlight.

No really satisfactory explanation of the gegenschein has been given on this hypothesis of the zodiacal light. The one usually given is that the particles composing the zodiacal light are in "full" phase when opposite the sun and therefore reflect enough more light to produce the effect of the gegenschein. The problem deserves further study.

CHAPTER XIV

COMETS AND METEORS

COMETS

293. The members of the solar system which we have been considering thus far are characterized by orbits of moderate eccentricity which, for the most part, have small inclinations to the plane of the ecliptic. They are also bodies of spherical or nearly spherical shape and of considerable density.

The comets which occasionally appear are very different from the planets and seem to resemble them only to the extent that they move under the influence of the sun's gravitation.

294. Designation of Comets.—The first comet discovered in any year is now usually designated by the year, the letter *a*, etc. Thus the comet discovered by Morehouse in September, 1908, was first designated comet 1908 *d* (Morehouse). If there are two independent discoverers both names are used. After the orbits have been computed and the times of perihelion passage determined they are numbered in the order of the time they came to perihelion. Comet 1908 *d* accordingly became 1908 III (Morehouse), since it was the third comet to pass perihelion in that year, although the fourth in order of discovery.

The greatest number of comets discovered in any year was eleven in 1925 so that the letters from *a* to *l* were used, the letter *i* being omitted by general agreement.

Sometimes it is not possible to determine the discoverer with exactness, and so the name is omitted. At other times the name given is not that of the discoverer but of some investigator who made a careful study of the comet, such as computing the orbit, etc. Thus in Sec. 301 it is stated that Messier discovered a comet in June, 1770, but it is called Lexell's comet, for the latter studied its orbit with care, found where it had been previous to discovery, where it went after it was lost to sight, etc. Other instances of this sort are Halley's comet and Encke's comet.

295. Appearance of Comets.—When a comet is visible to the naked eye there can be distinguished a bright and fairly well-

defined head and a tail, which is merely a continuation of the head, whose brightness diminishes with increasing distance from the head. At times the tail is only a degree or two in length, while at other times it extends to over 100°.

When the head of a large comet is examined with a telescope it usually reveals a bright, almost star-like, center which is called the *nucleus*, and a fainter enveloping material which is called the *coma*. At times the coma is seen to be composed of distinct layers of material, as shown in Fig. 129, which is a copy of one of Bond's drawings of Donati's comet in 1858.

FIG. 129.—The head of Donati's comet of 1858. (*From a drawing by Bond.*)

The tail of a large comet is a most unsatisfactory telescopic object, as it is so large that only a small portion is in the field of view at any one time.

The modern method of photographing comets with special cameras of wide field has shown much structure in the tail which is invisible both to the unaided eye and through the telescope.

The tails of large comets frequently show a dark stripe down the middle, although occasionally this central part is brighter than the adjacent portions of the tail.

296. Dimensions.—Comets are the largest units of the solar system. The diameter of the head may vary from 29,000 km (18,000 miles), as in the comet 1845 V, to 1,840,000 km (1,150,-000 miles) in the great comet of 1811. The tails of some comets

have exceeded 160,000,000 km (100,000,000 miles) in length and in the great comet of 1843 the tail at one time measured 320,000,000 km (200,000,000 miles). Even the nuclei of comets are of appreciable size, ranging from about 50 km (30 miles) for the comet of 1806 to 13,000 km (8000 miles) for comet 1845 III.

297. Changes in Comets.—One of the most conspicuous changes which most comets undergo is the development of a tail. When at a considerable distance from the sun and visible only in the telescope a comet does not appear to have a tail. As it approaches the sun the tail[1] begins to form and increases in size until about the time of perihelion passage. Thereafter it becomes smaller and smaller until it disappears from view.

A second change occurs in the dimensions of the head. In this instance the head diminishes in size as perihelion is approached and increases in size after perihelion passage. The head of Encke's comet in 1838 had a diameter of about 450,000 km (280,000 miles) when about 200,000,000 km from the sun. Near perihelion, when its distance from the sun was a little over 50,000,000 km, the head shrank to a diameter of 5000 km. Other comets besides Encke's show similar changes in the dimensions of the head, although the changes may not be so great.

A third change occurs in the nucleus. This frequently varies in brightness in an irregular manner. Often a nucleus is not visible until the comet is near the sun, but this is not an invariable rule.

298. The Direction of the Tail.—For the most part the tail of a comet is pointed away from the sun so that on approaching this body the tail follows the nucleus while on receding from the sun the tail precedes the nucleus. Occasionally, a comet may have more than one tail and the supplementary tails may make a considerable angle with the line pointing away from the sun. In comets 1880 VII, 1910 *a* and some others, one tail pointed toward the sun.

The general rule that a comet's tail is directed away from the sun indicates some influence which resides in the sun.

299. Orbits.—Kepler supposed that comets move in practically straight lines and wander through space from star to star. Somewhat later it was assumed that the orbits were parabolic, and Doerfel showed this to be the case for the comet of 1681. After the announcement of Newton's law of gravitation and his

[1] Some small comets never develop tails.

development of a method to determine the elements of comet orbits, his friend, Halley, calculated the parabolic orbits of all comets whose observations were known to him. He found that at intervals of about 75 years a brilliant comet had appeared and the computed orbits were essentially alike. This led him to conclude that, in reality, he had to do with the same comet which moved in a long ellipse instead of a parabola and predicted that it would reappear in 1759. It came as predicted and has also been observed at the subsequent returns in 1835 and 1910. Halley therefore has the credit of being the first to find an elliptic orbit for a comet which has since then been known as Halley's.

Since Halley's time many other elliptic orbits have been found and it has been shown that the number of elliptic orbits is roughly proportional to the length of time the comets have been observed, so that it is very probable that practically all orbits are elliptical. The periods thus far known range from 3.3 to over 1000 years.

A few comets have had hyperbolic orbits in the neighborhood of the sun, but calculations by Strömgren have shown that they were originally ellipses and had been changed to hyperbolas by the perturbations of the larger planets.

We therefore conclude that comets are really members of the solar system just as much as the planets, except that, in general, their orbits are very elongated ellipses.

The reason for the difficulty in determining the exact orbital elements of comets lies in their great eccentricity. Most comets are not discovered until they are near both the sun and the earth, and after perihelion passage they cannot often be followed very much beyond the earth's orbit unless they happen to be favorably situated. The small portion of their total path which lies within the earth's orbit may be very much alike for either a long ellipse, parabola or hyperbola, and very exact observations extending over some months may be necessary to decide the type definitely. If such observations are not available the difficulty is nearly unsurmountable.

Short-period ellipses are comparatively easy to determine, but when the period extends beyond a few hundred years a real difficulty usually exists.

The perihelion distances of known comets range from about 4.18 astronomical units for comet 1925 *a* (Shajn-Comas Sola) to 0.005 for the comets 1843 I and 1880 I. Very few have perihelion distances exceeding 1.5.

The inclinations of the orbits have all values, the number of direct and retrograde motions being nearly equal.

Physical Considerations

300. Density.—The fact that stars can be seen practically undimmed through the tail of a comet 1,000,000 km in diameter is strong evidence of the extreme tenuity of the material. Ten kilometers (6 miles) of air at sea-level density will show marked absorption effects, hence it is evident that the mean density of the tail is of the order of 0.00001 that of air at sea-level. The denser portions of the coma are also quite transparent to starlight, and only the nucleus seems dense enough to obstruct much light. In 1910, when the head of Halley's comet passed between earth and sun, nothing could be seen projected against the sun's disc. In view of these considerations it is evident that the mean density of the usual comet is extremely low. The only portion which may have an appreciable density is the nucleus, but no method of determining it has been devised.

301. Mass.—At present we are compelled to attack this problem in a negative manner.

1. No effect of the presence of a comet has ever been detected by any perturbations in the movements of the planets. Biela's comet, Lexell's comet of 1770 and some others have passed sufficiently near the earth to have their periods changed by some weeks, but the year was not affected in a measurable amount, that is, not even by as much as a second. Had their mass been as much as 0.00001 that of the earth, they would have produced appreciable effects.

2. The comet discovered by Messier in June, 1770, but since known as Lexell's comet, came very close to Jupiter in 1779, and comet 1889 V (Brooks) passed through the satellite system of Jupiter in 1886 without changing the satellite periods by a measurable amount. Lexell's comet was so strongly affected that it has never been observed since, and the orbit of Brooks' comet was greatly changed. The masses of these comets must, therefore, have been exceedingly small.

302. Spectrum.—The spectrum of a comet is not simple. There is a continuous spectrum with some absorption lines which appear to be merely reflected sunlight. This indicates the presence of sufficiently large solid particles to reflect the light.

More conspicuous, however, is a spectrum of bright bands, one in the yellow, one in the green and one in the blue (Fig. 130). This spectrum is identical with that of the blue flame of a Bunsen burner. These bands appear to be due to carbon monoxide. Besides these there are some bands due to cyanogen. Occasionally, bright sodium and magnesium lines are seen and on one occasion there were thought to be some bright iron lines.

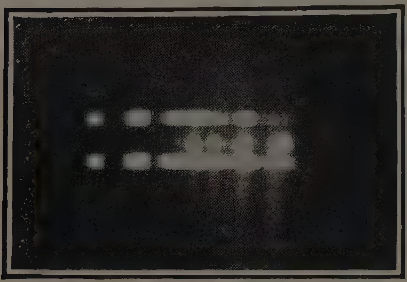


FIG. 130.—Spectrum of comet Morehouse, Nov. 4, 1908, with comparison spectrum of helium and nitrogen. (*Photographed at the Yerkes Observatory.*)

In general, the bright bands are much more intense when the comet is near the sun and metallic lines are visible only near the time of perihelion. The brightness of the spectrum is subject to considerable variation.

303. Internal Motions.—The layers of the coma as shown in Fig. 129 are not stationary. They appear to come from the sunward side of the nucleus as puffs of matter, possibly gaseous, directed toward the sun, which are then driven backward into the tail. Sometimes several of these puffs may be seen enveloping the nucleus and they are known as *envelopes*.

In other cases, as shown in Fig. 131 of comet Morehouse, a very large amount of material is emitted from the nucleus to form a dense portion of the tail. This eruptive material then moves outward toward the end of the tail and finally is lost to view. Sometimes secondary tails develop and then disappear, only to be replaced by others.

The nucleus itself undergoes changes of shape and has been known to divide into a number of parts, as in comet 1882 II, and into two parts, as in Biela's comet in 1846. The latter comet actually divided into two complete individuals.

304. The Light of Comets.—As stated in Sec. 302, some of the light of comets is merely reflected sunlight, but the bright bands and lines in the spectrum come from self-luminous material probably ejected from the nucleus. As the comet approaches the sun, the sunward side of the nucleus probably absorbs some heat, and gaseous material within the nucleus is driven out. This material is then not only illuminated by the sun, but becomes self-luminous, probably due to the action of the sun. It seems likely that this solar action is of an electrical nature, somewhat

like the terrestrial aurora which seems to be caused by streams of electrified particles given off by the sun entering the upper regions of the earth's atmosphere and rendering gases in those regions luminous.

305. Tail Formation.—In addition to the probable electrical action noted in the preceding section, the sun appears to exert a force which drives away the material ejected from the nucleus thus forming the tail. The exact nature of the action is not

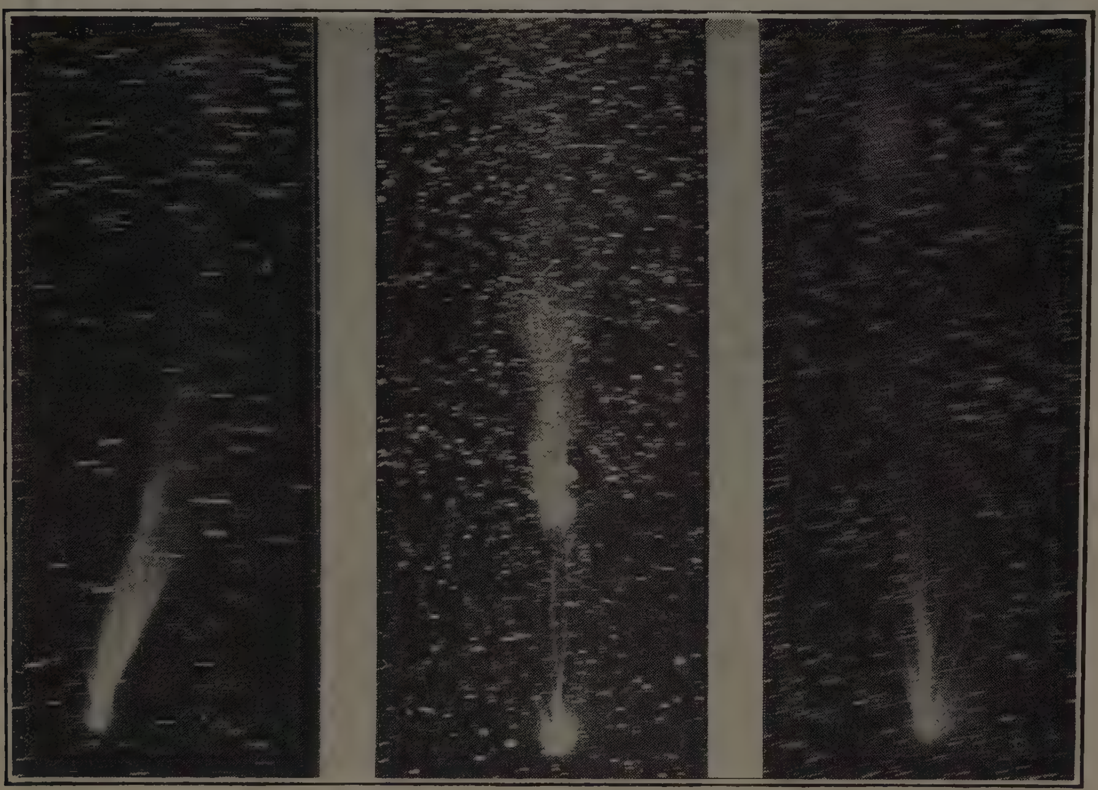


Fig. 131.—Comet Morehouse, Sept. 30, Oct. 1 and 2, 1908, showing material being driven away from head of comet. (*Photographed by Barnard at the Yerkes Observatory.*)

wholly clear, but two forces are probably at work, one of an electrical nature and the other light pressure.

If the sun and the particles of the tail have similar electrical charges, a repulsion would result which might be stronger than the gravitational attraction and thus force the charged particles away from the sun.

Many years ago Clerk-Maxwell predicted that light waves would exert pressure when they fell on a surface. This pressure was first observed by Lebedew in 1900, and a little later Nichols and Hull in this country were able not only to observe but also to measure it. Their measurements showed

values agreeing very closely with the pressures calculated on theoretical grounds.

Using these measurements Schwarzschild calculated the relation between the sun's light pressure and gravitation on particles of various sizes on the assumption that they were as dense as water. His results show that for diameters between 0.0015 and 0.00007 mm light pressure is greater than gravitational effects, while for values outside these limits the gravitational effect is the greater. At one point between the limits given, light pressure is 18 times as effective as gravitation. These results refer to solid particles. The presence of a light-pressure effect has also been demonstrated for gases.

By making certain plausible assumptions, light pressure, a charged sun and possibly a charged nucleus seem to account for most of the phenomena seen in comets' tails, but the problem deserves further study before it can be considered properly solved.

306. What Becomes of the Tail.—From the way in which the material of the tail is driven away from the nucleus it is evident that it is finally lost to the comet. The tail of a comet may therefore be likened to the locomotive smoke which is continuously left behind. In consequence, the comet must be diminishing in mass and we would expect that a periodic comet, coming repeatedly into the neighborhood of the sun, would ultimately waste away. This has occurred in the case of some periodic comets, but it does not seem to be an invariable rule.

307. The Nature of a Comet.—The evidence presented thus far leads to the conclusion that at least the coma and the tail consist of very small particles, probably gaseous, and these parts might therefore be called nothing more than a very diffuse gas cloud with possibly some finely divided dust. The nucleus, however, seems to be composed of denser material, probably solid parts. In view of the fact that a number of comet nuclei have been seen to break up and others change in shape and size, the nucleus is apparently made up of a mass of separate parts and is not a single solid mass. The evidence seems to favor the view that the nucleus is probably a mass of comparatively small particles loosely bound together by their mutual gravitation—as one astronomer expresses it, "a gravel bank." Such a mass could be disrupted easily by the sun. Additional evidence will be available when we consider the relation between comets and meteors (Sec. 325).

308. Comet Families.—An investigation of the location of the orbits of the short-period comets shows a curious relationship to the orbit of Jupiter (see Fig. 132). In each instance the aphelion point of the orbit lies close to Jupiter's orbit. About 30 comets of this group are known, but authorities differ in their

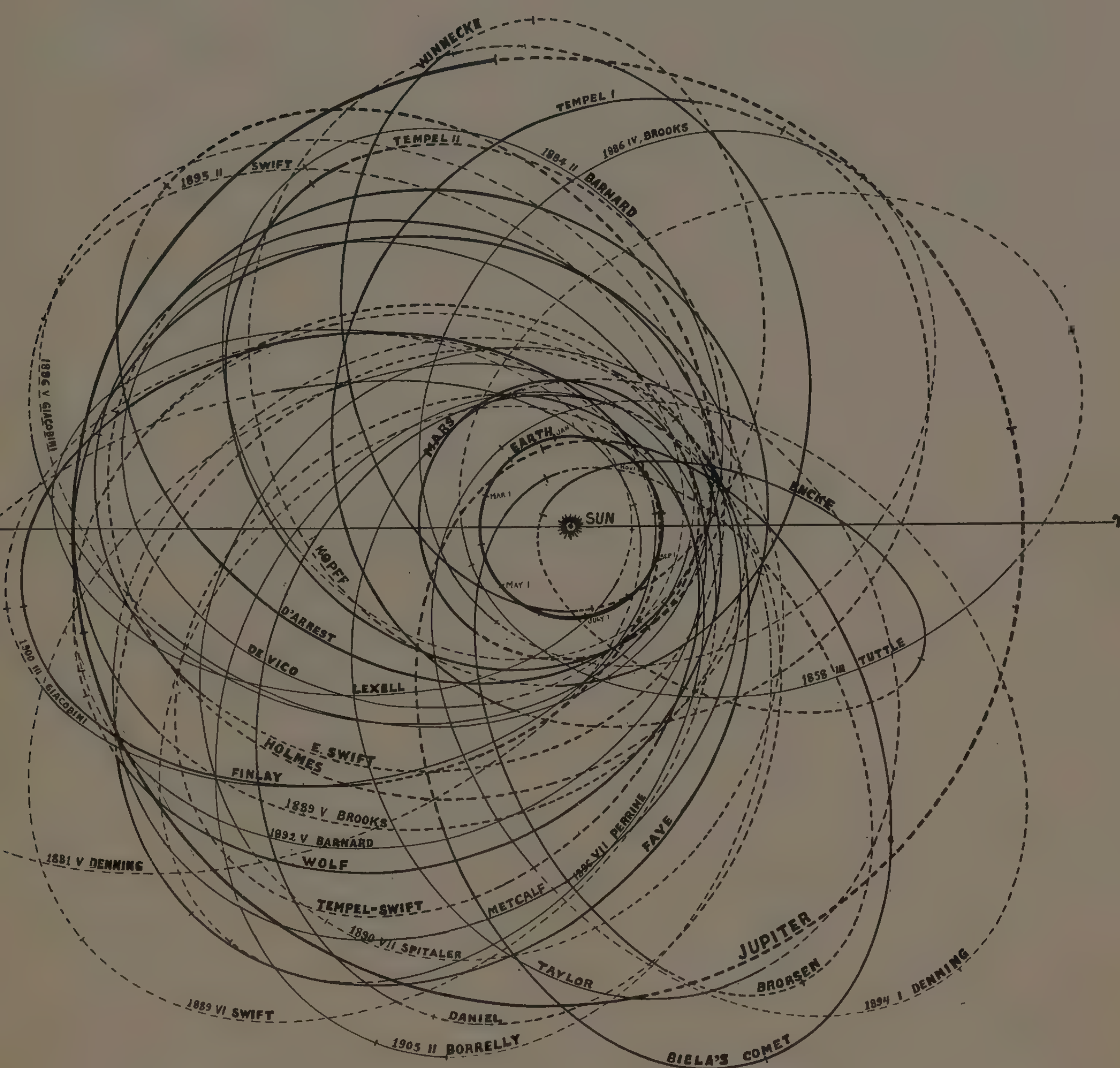


Fig. 132.—Jupiter's comet-family. (*From Popular Astronomy.*)

opinions in the cases of some comets which either have been observed only once or which apparently have been lost. Such a grouping of comets is referred to as a *comet family.*

Saturn, Uranus and Neptune also possess comet families of one, two and six members respectively, if we accept Flammarion's grouping.

The usual explanation for the existence of such families is the so-called "capture" theory, which is as follows:

The usual orbit of a comet is a long ellipse. At one of its approaches to the sun it passed so near the planet that its motion was retarded and the orbit altered into a short-period ellipse. Whether or not this explanation is the true one may still be a question.

Various comet families consisting of the comets whose aphelia lie beyond Neptune's orbit have been formed by various investigators in the hope of revealing the existence of a planet beyond Neptune. The comets selected, however, seem to depend more upon the investigator than upon the orbits, and nothing has resulted up to the present time.

309. Comet Groups.—There are a number of instances on record where the orbits of several comets are so nearly alike that one may be justified in saying that several comets are moving in a single orbit. These are called *comet groups.*

It is possible that the members of a group were once portions of a single comet which has been broken up by repeated approaches to the sun. Such a division has been seen to occur in the case of several small comets, but the companion comets have either disappeared or the entire comet has been lost, so that the explanation is merely a working hypothesis.

Some Remarkable Comets

310. Halley's Comet.—As stated in Sec. 299, this comet is the first for which an elliptic orbit was calculated. Halley had calculated the orbit of the great comet of 1682 and found that it was essentially the same as the orbit of a bright comet seen in 1607. Since he thought it very improbable that two comets should move in the same orbit, he concluded that it was very probably the same comet. On looking up records at intervals of about 75 years he found reports of bright comets in the years 1531 and 1456. From the descriptions available they too moved in the same orbit as the comet of 1682. He therefore concluded that the comets of these various years were returns of the same comet at approximately 75-year intervals. He accordingly predicted a return for 1758. Owing to perturbations of the comet's orbit by Jupiter and Saturn, it did not come until the following year. It was likewise seen in 1835 and 1910.

While calculating the return for 1910, Cowell and Crommelin examined many ancient records and were able to trace back the comet's history with certainty to 87 B.C., and it is probable

that it was also seen in 240 B.C. The interval between successive returns of the comet to the sun varies somewhat in length owing to planetary perturbations, but it has not differed much from 75.5 years.

At perihelion the head of the comet is at a distance of 0.59 astronomical unit from the sun, but at aphelion the distance becomes 35.3, over five units beyond the orbit of Neptune.

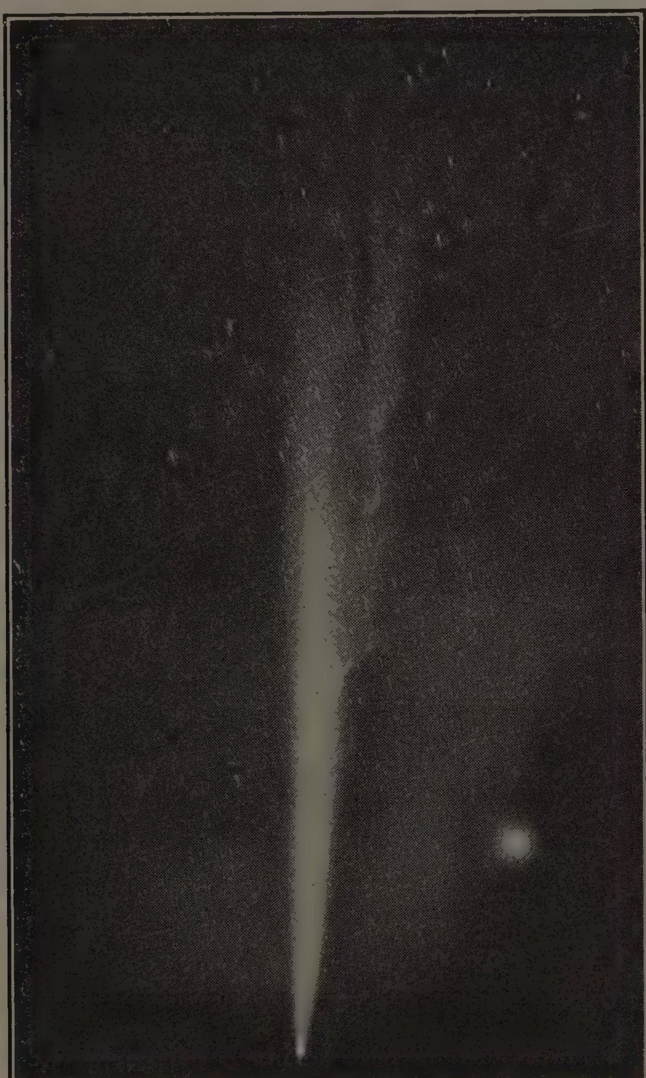


FIG. 133.—Halley's comet as photographed at the Lowell Observatory, May 13, 1910. The bright object near the head of the comet is the planet Venus.

The appearance of the comet as seen by the author about the middle of May, 1910, in California is as follows:

Shortly before dawn the head of the comet was just above the eastern horizon. Its diameter was about one-fourth of a degree. The tail was practically straight and stretched across the sky a distance of at least 130°, ending in the southwest quadrant.

The tail gradually widened as its distance from the head increased until at the end it was about 12° in width. Near the head the tail was very bright (Fig. 133) but became fainter with increasing distance, until near the extremity it was about as bright as the fainter parts of the Milky Way.

311. The Great Comet of 1744.—This comet was seen in the morning sky near the rising sun. Late in February two tails were noted, but after a week of cloudy weather in Europe there became visible a wonderful comet of six tails, each over 30° long. During this portion of the apparition the head was below the eastern horizon, so that the comet could not be seen as a whole, but even so the meager reports available show clearly that this must have been one of the most remarkable comets of all time.

312. The Great Comet of 1811.—This comet was discovered in March, 1811, and last seen in August, 1812, an exceptionally long period for any comet. In the autumn of 1811 it was visible practically all night in northern latitudes because of its position far north of the celestial equator. The greatest length of tail was about 25° and its breadth about 6°. The actual maximum length of its tail was about 160,000,000 km (100,000,000 miles) and the diameter nearly 25,000,000 km (15,000,000 miles). The orbit computed by Argelander gave a period of slightly over 3000 years with an aphelion distance of about 65×10^9 km (40×10^9 miles), or 14 times the distance of Neptune.

313. The Great Comet of 1843.—This comet was first seen in the southern hemisphere late in February and became visible in north temperate latitudes about the middle of March. The tail was about 40° in length, about 1° in width and practically straight. The perihelion distance of this comet is the smallest on record, about 800,000 km (500,000 miles), so that the head was only a little over 100,000 km from the sun's surface as it swung round this body.

314. Biela's Comet.—This comet should not be classed as remarkable on account of its size but because of its history. An Austrian officer named Biela discovered a faint comet on Feb. 27, 1826, which had a period of about 6.7 years and which soon proved to be one seen also in 1772 and 1805. A calculation showed that in 1832 the comet would pass within 30,000 km (20-,000 miles) of the earth's orbit about a month before the earth reached the same point. The comet was seen on its return in 1832 but not the next time, in 1839, because its position was too

near the sun as seen from the earth. On the next return it was first seen in November, 1845. In January, 1846, it began its remarkable changes by dividing into two parts, a brighter and a fainter comet. By March they had separated to a distance of 300,000 km. The fainter one could be followed for over 2 months and the brighter 3 months. In 1852 both comets were again seen, but then about 2,500,000 km apart. The return of 1859 was unfavorable like the one in 1839, so that special efforts were made to see them in 1866, but in vain. In 1872 the comets should have been most favorably situated for observation, but again the search was unrewarded, and they have never been seen since. On Nov. 27, 1872, when the comets should have been very near the earth, a shower of shooting stars was observed coming from the region of the sky where the comets should have appeared. Possibly these were the remnants of the disintegrating comet. The matter will be considered again in a later section.

FIG. 134.—Comet 1910 I as photographed at the Lowell Observatory, Jan. 28, 1910.

315. Comet 1908 III (Morehouse).—This comet was discovered photographically by Morehouse at the Yerkes Observatory on Sept. 1, 1908. It presented many features which distinguished it from the ordinary comet. It was very bright photographically, although faint visually, as its light was predominantly from the blue region of the spectrum. The tail showed many changes and was often markedly different in the course of a few hours. Sometimes the tail was of the ordinary type and then an eruption of substances from the head would furnish material for a number of streamer-like tails which appeared to have curves and twists. At other times a puff of material would leave the head and be

driven backward along the tail. Changes of this character were frequent and of extraordinary interest as showing the complexity of cometary phenomena (Fig. 131).

316. Comet 1910 I.—In January, 1910, a comet of exceptional brightness was discovered simultaneously by a number of persons in South Africa. It was so bright that for a short time it could be seen in full daylight near the sun with the unaided eye. A few days after discovery it became visible in the evening in the northern hemisphere and was a wonderful sight in the western sky (Fig. 134). It presented a broad and moderately curved tail nearly 40° in length, a shorter, narrower tail pointing in nearly the same direction as the main tail and a very short tail, about a quarter of a degree in length, pointing directly toward the sun. Within a few weeks it became too faint to be seen with the unaided eye but it could be followed telescopically until July of that year.

METEORS

317. General Appearance.—On any clear moonless night an observer may see an occasional swiftly moving point of light which remains visible for 1 or 2 seconds and then vanishes (Fig.

FIG. 135.—A meteor photographed at the Yerkes Observatory, June 7, 1899.

135). These vary in brightness from that of the full moon to the limit of visibility in a telescope. They vary in color from a bluish white through white to yellow, green and reddish. The fastest moving are bluish white and the slowest are reddish.

Occasionally, they leave trains which endure from a second or two to an hour. Such objects are known as shooting stars or meteors.

Occasionally, much larger bodies, often called fire-balls, are seen, fragments of which reach the earth's surface. There is reason for believing these to be different from the ordinary meteor or shooting star and they will be considered later under Meteorites.

318. Altitude and Velocity.—If two observers, stationed from 15 to 50 km apart, observe the same meteor with reasonable accuracy it is possible to determine the height and velocity in accordance with the principle illustrated in Fig. 136, where A and B are the observers and CD the path of the meteor. Observations of this character have been carried out many times. The altitude of the beginning of the meteor path varies from about 100 to 135 km (60 to 85 miles), of the end from about 60 to 80 km (40 to 50 miles). The paths are of the order of 100 km (60 miles) in length and the velocity ranges from about 25 to nearly 80 km (15 to 50 miles) per second.

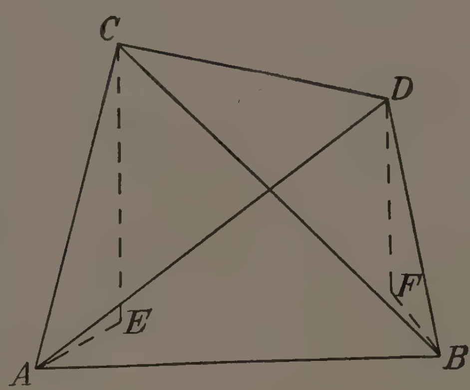


Fig. 136.—Determining the height and velocity of a meteor by observers at A and B. Each determines the direction of the beginning and end of the meteor path and the time during which it is visible. From these data, and using the triangles involved, the heights CE and DF, the length of path CD and the velocity are determined.

319. Luminosity.—The high velocity of meteors explains their luminosity. When a small particle moving at such a high velocity strikes our upper atmosphere great friction and air pressure result. This heats the surface to incandescence and the molten material is stripped off as soon as it is formed. The degree of heat depends upon the initial velocity, the fastest ones becoming white hot, while the slowest attain only a red heat.

The luminosity of the meteor train has been shown by the late Professor Trowbridge of Columbia to be, in all probability, an electrical phenomenon known as the *afterglow* which can be duplicated in the laboratory. The ionization of the rarified air on this hypothesis would be caused by the intense heat at the surface of the meteor.

320. Size.—The disappearance of almost all meteors at considerable heights above the earth's surface indicates that they

must be comparatively small particles of matter. All determinations of their mass rest upon certain assumptions which are difficult of proof, but it appears reasonable to assume that the largest of those ordinarily seen are not likely to weigh much over 1 gram (1/30 ounce) and the smallest must be mere grains of sand or specks of dust.

321. Probable Number.—The number of meteors striking the earth's atmosphere daily is very great. A single observer may average about 10 per hour. Owing to the curvature of the

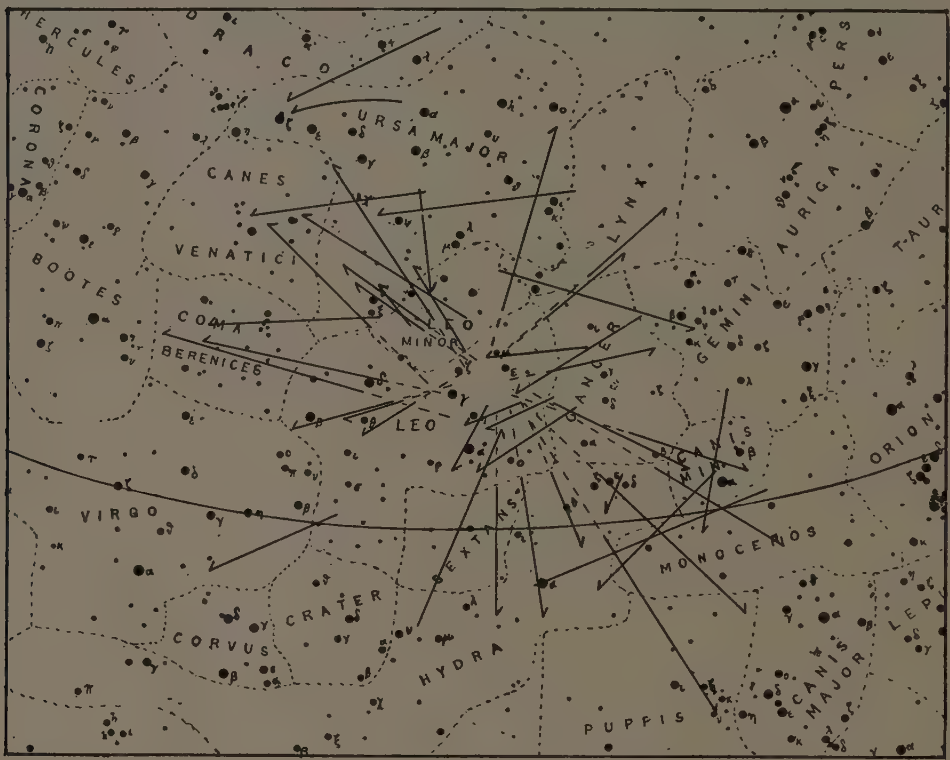


FIG. 137.—Meteors observed at the Goodsell Observatory Nov. 15, 1900. About two-thirds of them are seen to radiate from a small area in Leo.

earth's surface, the height at which they are observed, atmospheric absorption and their brightness, it is not likely that any are visible to the unaided eye at distances over 500 km. Some years ago Prof. H. A. Newton of Yale estimated that from 15,000,000 to 20,000,000 bright enough to be seen with the naked eye enter the earth's atmosphere daily. If we include the telescopic meteors the numbers will be considerably higher.

322. Radiants.—Meteors may be seen at the rate of about six to ten per hour on almost any good night in various parts of the sky, but at times a much larger number may be observed. Such

an increased number is designated a meteor shower. When the paths of the individual meteors of a shower are traced backward it will be found that they intersect in a small area in the sky. Such an area is known as a *radiant* and may be only a degree or two in diameter (Fig. 137).

Meteors are named according to the location of their radiants. The Leonids come from a radiant in Leo, the Perseids from Perseus, etc.

Most of the meteor paths appear as straight lines coming from the radiant. The explanation of this appearance is that they are moving in parallel lines for which the radiant is merely the vanishing point. A few of the best-known radiants with the dates when they are most active, according to Denning, are the following:

TABLE VI

Name	Radiant		Date
	R.A.	Dec.	
Lyrids	270°	+33°	Apr. 20
Perseids	45	+57	Aug. 11
Leonids	150	+22	Nov. 14–15
Geminids	111	+33	Dec. 11–12

The radiant does not show the actual direction in space from which the meteors come, since the apparent motion is the resultant of the meteor's own motion and the motion of the observer with the earth. The method of determining the actual direction lies beyond the scope of this book.

323. Meteor Orbits.—From a knowledge of the position of the radiant and the direction of the earth's motion it is possible to compute the orbits of meteors with respect to the sun. These prove to be ellipses about the sun, usually of considerable eccentricity, and intersecting the orbit of the earth. When the earth and a meteor are near the intersection of the two orbits at the same time the attraction of the former draws the meteor from its orbit, it plunges into the earth's atmosphere and is destroyed. Figure 138 shows the orbit of the Leonids which appear from Nov. 12 to 17.

324. Meteor Showers.—When a swarm of meteors travels about the sun each meteor has its own orbit, those nearer the

sun moving faster than those farther away. The path of the densest portion of the swarm is the one to which the term "orbit of the swarm" is applied.

If the meteors are distributed quite evenly around the orbit a shower may be expected each year when the earth reaches the intersection of the two orbits, but if the meteors are grouped in a swarm then a shower is possible only when both earth and swarm reach the intersection at the same time.

The best-known case of a swarm is that of the Leonid meteors. These were first especially noted on the night of Nov. 11 to 12, 1799, when many thousands were seen in the course of about 4 hours. In 1833 they again appeared, especially to North

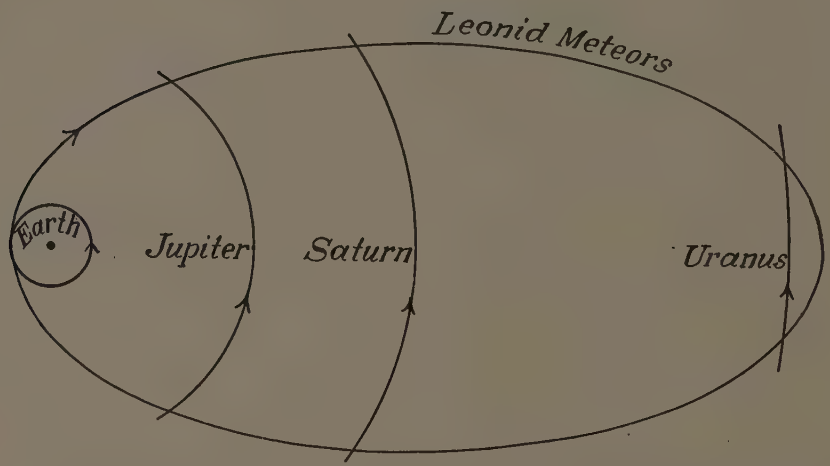


FIG. 138.—The orbit of the Leonid meteors. The plane of the orbit is inclined 17° to the plane of the ecliptic.

American observers. One observer states that during the height of the shower the meteors appeared "like a snow fall to the earth," and another estimates the rate after the maximum was past as about 10,000 per hour. In 1866, European observers saw a splendid display, although it was by no means equal to that of 1833. At Greenwich eight observers covered the sky and counted a total of 8000, with a maximum of 4860, between one and two in the morning. Great expectations were therefore aroused for the expected return in 1899, but the results were rather disappointing, as only comparatively few were seen. Better displays occurred in 1900 and 1901, but they were not remarkable. Perturbations by the larger planets seem to account for this. It will be well to watch for them in 1932 and 1933.

Each year a few Leonids are seen, so that there must be some scattered all the way around the orbit in addition to the main swarm which completes its circuit in 33 years.

325. Relation between Comets and Meteors.—In 1866, Schiaparelli computed the orbit of the August meteors, the Perseids, and compared the elements with those of the bright comet seen 4 years previously, Comet 1862 III. The similarity was striking. Shortly thereafter Leverrier found a marked similarity between the orbit elements of the Leonids and Comet 1866 I. In 1867, Weiss found a third case in that of the Andromedes and Biela's comet and a fourth in that of the Lyrids and Comet 1861 I; various observers and computers from 1868 to 1910 gradually established a fifth for the Aquariids and Halley's comet and in 1916 Olivier and Denning independently found a sixth between the meteors from a radiant near η Ursæ Majoris and the Pons-Winnecke comet.

These six cases are the only ones known up to this time where the connection is reasonably certain. This connection may be stated as follows: In at least six cases comets and meteor swarms travel in essentially the same orbits about the sun. This indicates an intimate connection between the two which may throw considerable light on the nature of comets.

Biela's comet was seen in 1846 to break into two parts, which had separated about 2,500,000 km by 1852. The comet should have been seen in 1872 but was not, and has never been seen since. At about the time of closest approach in 1872 and again in 1892 when the comet should have been near the earth, fine meteor displays were observed coming from the region where the comet should have been. It therefore appears possible that the comet was broken up and the remnants appeared as meteors.

The small mass of all comets can be explained if we assume that their nuclei are nothing more than compact meteor swarms. This cannot be definitely proved but appears probable. It explains the ease with which comets appear to break up as well as the reason for the disappearance of some comets, and possibly indicates the ultimate fate of all.

If we accept this view it does not necessarily follow that all meteors originate from comets, as there may be other sources as well. These sources appear connected with the solar system, as the meteor orbits are elliptical. If they lie outside the system the orbits should, in general, be hyperbolic.

METEORITES

326. Definition.—From time to time large meteors are noted which strike the earth. They are sometimes called fire-balls when seen in the sky. The portions which reach the earth's surface are called *meteorites.*

327. Phenomena of Fall.—The usual events when such a large meteor is seen are as follows: First there is a brilliant flash of light which lasts as long as the meteor is visible, but which may fluctuate in brightness. Sometimes it breaks into several parts. Frequently a luminous train is left which may persist upwards of an hour and which will become bent and broken by the air currents encountered. If the fall occurs in the daytime the train looks like smoke. Sounds like rolling thunder or the crackling of rifle fire, accompanied by explosions which may be violent enough to shake buildings, are usually heard. The color varies, like that of shooting stars, from a bluish white to a dull red. Sometimes the meteorites reach the earth's surface with sufficient velocity to bury themselves several feet in the earth,[1] while at others they hardly dent the ground.

328. Meteorite Showers.—In some instances only a single meteorite is found, while in others the number of individual pieces runs into the thousands. In the latter case most of the pieces are small. When the number is large they are usually found over an elliptical area, the longer axis of which is in the direction of motion. This area was 16 miles long and 3 miles wide in the Khairpur fall of Sept. 23, 1873, in India. It is not impossible that the individuals of such a fall were separated before striking the earth's atmosphere, but in the light of our present knowledge it seems probable that in the majority of cases the disintegration occurred within the atmosphere.

329. Temperature.—The temperature of the meteorite before it strikes the earth's atmosphere must be very low, possibly not far from absolute zero. The intense heating while passing through the air appears to be confined to the outer layers, the thin molten and vaporized layer being continuously stripped off by the rush of air. In the cases of many which were seen to fall and were immediately found, they could be handled easily. Other instances are known where they have fallen into stacks

[1] The largest mass of the Estherville, Iowa, meteorite shower weighing over 180 kg (400 pounds) buried itself 8 feet in a stiff clay soil. A depth of 11 feet was recorded in another fall.

of hay or other inflammable materials without setting them on fire. Young states that one which fell in India in 1860 was found in moist earth, half an hour after its fall, coated with ice. If the passage through the atmosphere lasts but a few seconds we would expect to find them comparatively cold, but if the duration of fall lasts for some minutes the heat undoubtedly penetrates the mass.

330. Size.—Meteorites vary in size from those of practically microscopic dimensions to that of the largest of the Cape York group of irons whose dimensions are about $3.3 \times 2 \times 1.5$ meters ($11 \times 7 \times 5$ feet) and which weighs 33,000 kg (36½ tons).

331. Length of Path in Atmosphere.—If the mass comes through the air practically perpendicularly to the surface of the earth the path noted may be only about 100 km in length. If it comes in at an angle, however, the path may be much longer. The longest path on record is that of a group of meteorites which were first noted near Regina, Sask., at an altitude of 57 km (35 miles) and which were last seen from a ship in latitude $-3°$, longitude 32°.5 west, at a height of 23 km (14 miles). This path measured 9100 km (5650 miles).[1] The average velocity over the entire path was about 8 km (5 miles) per second. Had these masses fallen on land and been found immediately, they would, undoubtedly, have shown a high temperature.

332. Classification.—Meteorites may be roughly divided into three classes: the iron meteorites, the stony-iron meteorites and the stone meteorites. The one kind gradually merges into the other, but for practical purposes this simple division into three classes will answer. About 700 meteorites are now known, according to Farrington. Of this number about one-half were seen to fall, the others being recognized by their general characteristics. Only 10 of the approximately 350 meteorites seen to fall have been irons.

333. Composition and Structure.—About 30 elements have thus far been detected in meteorites. Iron is the most important. This is always alloyed with nickel and sometimes with other metals. In no case has a new chemical element been found, but minerals not known on the earth are found in many meteorites.

[1] See reports on this remarkable group of meteorites in *Journal Royal Astronomical Society Canada*, vol. 7, p. 145 (1913); and *Popular Astronomy*, vol. 30, p. 632 (1922); vol. 31, pp. 96, 443, 501 (1923).

According to Merrill, the three classes have the following general composition:

Iron Meteorites.—These consist essentially of an alloy of nickel-iron with iron phosphides and sulphides. When these meteorites are etched with dilute acid they show a peculiar crystalline structure known as Widmanstätten figures (Fig. 140).

Stony-iron Meteorites.—These consist of an extremely variable network or sponge of metal, the interstices of which are filled with silicate mineral.

Fig. 139.—A large iron meteorite from Quinn Canyon, near Tonopah, Nev., and now in the collection of the Field Museum, Chicago. Weight 1486 kg. (3276 pounds). Note the pitted surface and conical form which is characteristic of meteorites. (*Courtesy of Field Museum.*)

Stony Meteorites.—These consist essentially of silicate minerals with minor amounts of metallic alloys and sulphides.

When a fragment of a meteorite is heated it gives off a number of gases. Those commonly found are hydrogen, nitrogen, carbon monoxide, carbon dioxide and methane.

334. Source of Meteorites.—Various authorities differ on this point. Some hold that the only essential difference between meteorites and shooting stars is one of size, while others believe there is a real difference in that the shooting stars are members

of the solar system while the meteorites come from regions outside the system. The principal argument of those holding the latter view is as follows:

The possibility of computing elliptic orbits for meteor swarms around the sun is conclusive evidence that these belong to our

FIG. 140.—Widmanstätten figures of the Shrewsbury, Pa., iron meteorite (*Courtesy of Field Museum.*)

FIG. 141.—Microscopic section of the Homestead, Iowa, meteorite (stony), $\times$ 44. (*Courtesy of Field Museum.*)

system. When it has been possible to compute the orbits of meteorites or fire-balls, however, these are found to be strongly

hyperbolic.[1] Hyperbolic orbits are conclusive evidence of cosmic origin, and therefore we must assume an essential difference between the two classes of meteors.

Whatever view one may take in this matter, the fact nevertheless remains that meteorites are the only samples of extraterrestrial substances that ever reach us and therefore deserve the most careful study of the scientific worker.

[1] Von Niessl finds this to be true for 154 cases which he was able to investigate (Smithsonian Miscellaneous Collections vol. 66, No. 16)

CHAPTER XV

THE STARS

335. The Constellations.—It is evident to anyone observing the night sky that the brighter stars can be formed into groups which facilitate the identification of the individual stars. The ancients did this too, many thousands of years ago, associating various groups of stars with their deities and heroes. Such groups of stars are called *constellations.*

At the present time about 88 constellations are recognized. Of this number 48 have come down to us from the time of Ptolemy (second century A.D.). The remaining 40 are largely modern and are found, for the most part, in the southern heavens, which were below the horizon of Alexandria where Ptolemy lived.

336. The Zodiacal Constellations.—These constellations are the principal ones crossed by the zodiac. In order, they are Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpio, Sagittarius, Capricornus, Aquarius and Pisces. Sun, moon and planets are therefore usually found within the borders of these 12 constellations.

337. Designation of Stars.—The ancients, in general, designated stars by their positions in the constellation figures, such as "the star in the head of the preceding of the twins," "the star in the heart of the lion," etc. Besides this they gave special names to hundreds of stars, the same star sometimes having more than one name. At the present time three methods are used: names, Bayer's letters and Flamsteed's numbers, and catalog numbers.

338. Star Names.—From 25 to 30 names of stars are in common use. These as well as others only infrequently used have come down to us from the Greeks, Romans and Arabs. For the most part these names refer to the brightest stars, such as Sirius, Canopus, Vega, Arcturus, but in a few instances they refer to relatively faint stars which are of special interest, such as Alcor and Merope.

339. The Bayer-Flamsteed System of Star Designation.—In 1603, Bayer of Augsburg published what is usually considered as

the first star atlas of general value. He arranged the stars in each constellation roughly in the order of brightness, and assigned to them the various letters of the Greek alphabet. Thus α Arietis is the brightest star of Aries, β Arietis the second brightest, etc. In some cases this arrangement was not followed, as, for example, in Ursa Major, where the letters were assigned in the order of the stars beginning at the front of the bowl of the Big Dipper and terminating at the end of the handle. When the Greek alphabet did not suffice he used the letters of the Roman alphabet in order.

About a century later Flamsteed, England's first Astronomer Royal at Greenwich, numbered the approximately 3000 stars he had observed according to constellations, and at the present time when a star has no Bayer letter, but a Flamsteed number, the number is used.

The letter or number of the star is combined with the genitive form of the constellation name in order to designate the star completely. Thus, α Orionis means α of Orion, etc.

340. Catalog Number.—Many catalogs of stars are now in existence, the stars being numbered according to the plan on which the catalog is constructed. Thus Boss 1234 is the star numbered 1234 in Boss' "Preliminary General Catalog," and A. G. Washington 673 is the star numbered 673 in the portion of the catalog of the Astronomische Gesellschaft observed at the Naval Observatory, Washington, D. C.

The brighter stars occur in many catalogs, in Bayer's atlas and also have special names. One star may therefore have quite a variety of designations. The one to be chosen in any instance will depend upon the conditions involved.

341. Star Atlases and Charts.—Following the atlas of Bayer there have been many others. Some give only the brighter stars, while others give all of them to the limit of naked-eye visibility. Atlases, in general, are for constellation study and the identification of naked-eye (sometimes called *lucid*) stars. Among the best of the modern ones may be mentioned those of Klein, Norton, Schurig and Upton.

Star charts, in general, are for the observing astronomer and show telescopic as well as the brighter stars. Some cover only portions of the sky, such as the Paris or Peters' Ecliptic Charts; others give only small isolated regions, like Hagen's Variable Star Charts; while others cover a large portion of the sky, such

as the Bonner Durchmusterung Charts, or the complete sky, such as the Franklin-Adams Charts, or the great project of the Astrographic Chart (Carte du Ciel).

Bonner Durchmusterung Charts.—These charts, 40 in number, show all stars to the ninth magnitude, and many still fainter, from the north celestial pole to 2° south of the celestial equator on a scale of 1° to 2 cm (¾ inch). They were published by Argelander of Bonn from 1857 to 1863. Over 300,000 stars are shown. The star positions were first obtained by visual observations with a small telescope and the charts engraved afterwards. The charts (Fig. 142) represent an enormous amount of work and are still of great value.

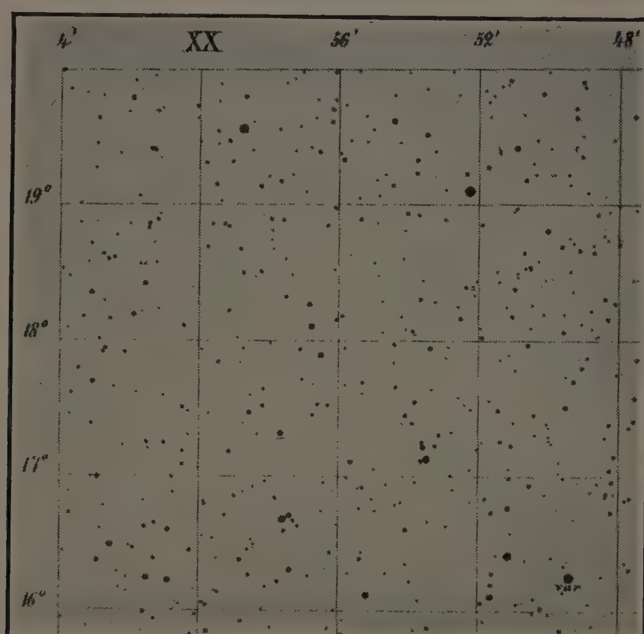


FIG. 142.—Small portion of one of the Bonner Durchmusterung charts. Scale ⅔ original scale. (*Courtesy of Bonn Observatory.*)

Some years later Schoenfeld continued the series of charts to declination 23° south, so that the B.D. covers practically all the sky visible at latitude 45° north.

Franklin-Adams Charts.—These charts, 206 in number, are photographic reproductions, on a scale of 1° to 15 mm (0.6 inch), of photographs covering the entire sky taken by the late Franklin-Adams of England. Each chart is a little over 15° square and shows stars down to the seventeenth magnitude, about the limit of visibility in the great Lick and Yerkes refractors. The photographs were taken with a 25-cm (10-inch) lens, especially designed for the purpose, with exposures of about 2 hours.

Astrographic Charts.—In 1887 an international astronomical conference was called at Paris to consider photographing the entire heavens on a most elaborate scale. It was decided to use photographic refractors of about 34-cm (13.5-inch) aperture and 3.4-meter (11.2-foot) focal length. The work was divided among 18 observatories scattered over most of the world. Each was to photograph about 1200 regions of the sky, each region being photographed twice, and then have charts made showing the stars thus photographed. The great project is not yet complete, although it has been pushed with considerable vigor and most of the plates have been taken. There is a possibility that the great chart with its millions of stars may never be completed because of the great expense involved in its publication.

342. Star Catalogs.—A star catalog is a list of stars together with their positions, usually in right ascension and declination, their magnitudes and such other information as may be desired. Some catalogs contain approximate positions of many stars, while others give exact positions of a relatively small number. A few of the important catalogs with brief descriptions follow:

The Almagest.—This is the earliest star catalog of which we have copies. It was made by Ptolemy of Alexandria about A.D. 138 and contains the longitudes and latitudes of 1028 stars together with the constellations in which they are located.

The Bonner Durchmusterung.—The charts made from this catalog were mentioned in the preceding section. The catalog itself is printed in four volumes and gives the approximate positions of nearly 460,000 stars between the north celestial pole and declination 23° south.

The Cape Photographic Durchmusterung.—The purpose of this undertaking was to continue the work of Argelander and Schoenfeld to the south celestial pole. Instead of making visual observations, however, Dr. Gill, the director of the Cape Observatory at Capetown, South Africa, elected to photograph the sky with a camera of large size, 15-cm (6-inch) aperture, and then determine the star positions by measuring the plates. The plates were actually measured by Prof. J. C. Kapteyn of the University of Groningen, Holland, so that the work represents a cooperative enterprise. Work was begun in 1885 and the final results published in 1899. The catalog, in three large volumes, gives the approximate right ascensions and declinations of nearly 455,000 stars between declination 18° south and the south

celestial pole. Gill was the first to show the great advantages of photography for star catalog purposes.

Astrographic Catalog.—This catalog is a part of the international undertaking referred to in the preceding section, being undertaken after Gill had shown the success of the photographic method. In addition to the plates taken for the chart, others of shorter exposure were to be taken on which the positions of the stars were to be measured with accuracy and a great catalog of stars provided. This catalog will ultimately be completed and give accurate positions and magnitudes of between eight and ten million stars over the entire sky.

343. Stellar Spectra.—Various classifications of stellar spectra have been used. The first was the work of Secchi at Rome who observed visually. Another system resembling Secchi's was developed by Vogel of Potsdam. The system now used almost exclusively was developed at Harvard by E. C. Pickering and his assistants while studying the photographic spectra of over 10,000 stars. The results of this study were published in 1890 under the title "The Draper Catalog of Stellar Spectra." In this work the spectra were grouped according to their appearance and letters from A to Q were assigned to the various groups. Further study has shown that some of the groups were not necessary and certain considerations to be stated later led to some change in the order of the letters. The order at the present time is as follows: O, B, A, F, G, K, M. The characteristics of these various classes will be stated briefly and one star named whose spectrum may be considered typical for the class.

O. There are two groups of O-type stars; the one shows bright bands due to hydrogen, helium and some other elements, and the other shows absorption lines of the same substances. The stars of the first group are often called Wolf-Rayet stars, because the first examples were discovered by Wolf and Rayet. The second group are known as the *absorption*-Otype stars (γ Velorum, ι Orionis).

B. The helium stars. Absorption lines of helium and hydrogen most prominent (δ Orionis).

A. Hydrogen stars. Most prominent absorption lines belong to hydrogen (Sirius).

F. H and K lines of calcium most prominent. Hydrogen lines next in prominence (δ Aquilæ).

G. Solar stars. H and K lines of calcium most prominent. Hydrogen lines no longer prominent. Many metallic lines (Sun).

K. Calcium lines still very prominent. Many metallic lines. Intensity of continuous spectrum decreases rapidly toward violet end (Arcturus).

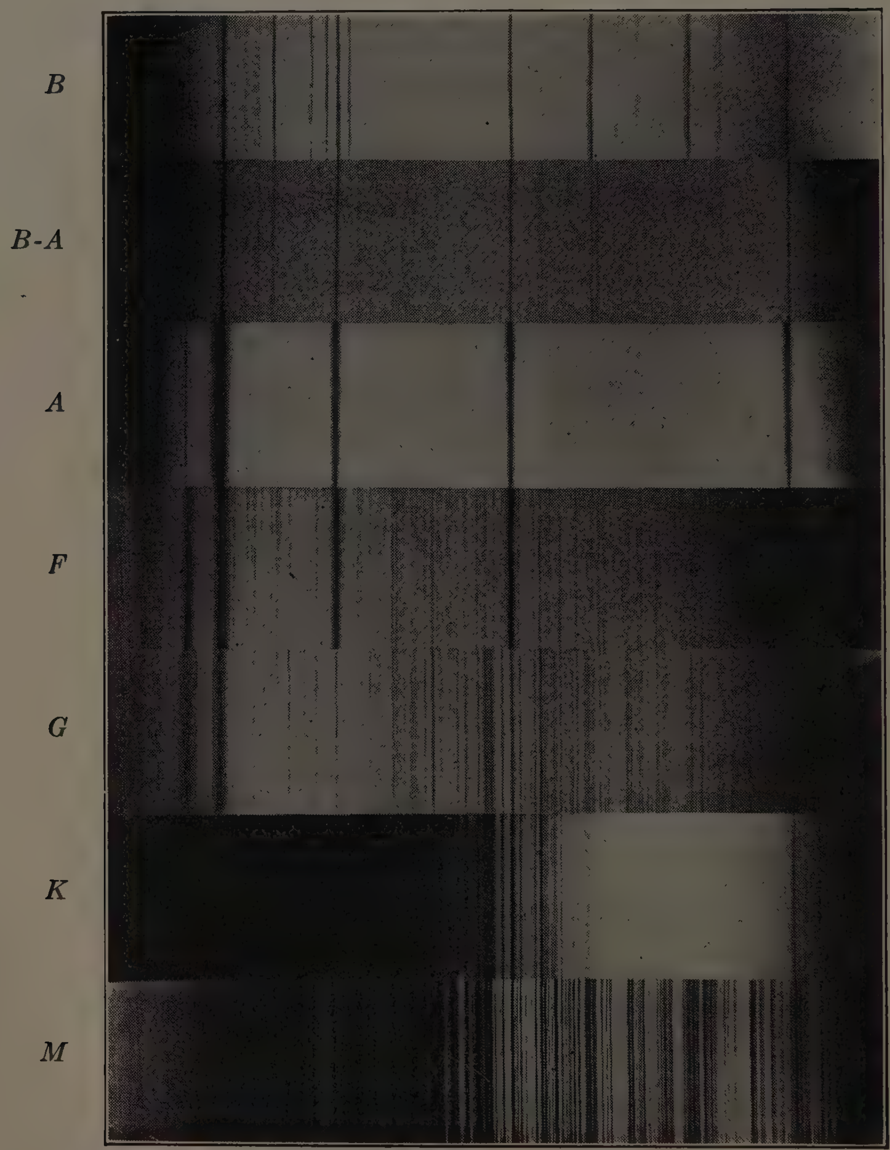


FIG. 143.—Stellar spectra, types B to M. (*Photographed at the Harvard Observatory.*)

M. Calcium lines remain prominent. Bands appear in green and blue regions. Violet end very weak (α Orionis).

Figure 143 shows the appearance of these types of spectra from B to M.

The series O to M represents seven general divisions of stellar spectra. Among the many thousands of spectra investigated there are found many slight differences in each group and one

group gradually merges into the next. Accordingly, subdivisions of these groups were made to indicate these gradations. In general, ten subdivisions were made and numbered from 0 to 9. The designation B5 means a spectrum 0.5 of the way from the first B spectrum to the first of the A group, and F8 a spectrum 0.8 of the way from the first of the F to the first of the G types. This subdivision of groups into tenths is carried out from B to K. In the M class only four subdivisions were made, and these are termed Ma, Mb, Mc and Md respectively.

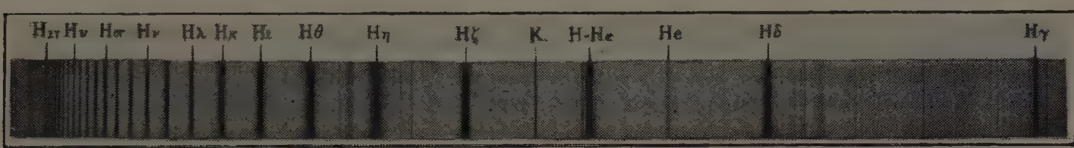


FIG. 144.—Spectrum of A-type star, Zeta Tauri, showing a remarkably fine series of hydrogen absorption lines. (*Photographed at the Detroit Observatory, University* of *Michigan.*)

344. Stellar Temperatures.—Until recent years this subject was based largely on conjecture, but it was evident that in the series from B to M the B stars must be the hottest and the M stars the coolest, since the first are almost a blue-white, while the second have a reddish tinge. When the laws underlying radiation came to be understood and the instruments and methods of observation became more refined it was found possible to obtain results in which we can have some confidence. The following table gives the results of the earlier determinations of Wilsing, Scheiner and Muench in one column and the more recent ones of Coblentz in another.

TABLE VII

Spectral class	Wilsing, Scheiner and Muench (199 stars)	Coblentz (17 stars)
B	10,400° Abs.	13,400° Abs.
A	9,700	10,000
F	7,000	7,000
G	5,200	5,800
K	4,200	4,300
M	3,150	2,900

The values of Wilsing, Scheiner and Muench were obtained by measuring the relative intensities of the various parts of the

spectrum while those of Coblentz were derived by observing the total radiation of the stars investigated by means of a delicate thermocouple. The agreement of the results by these two entirely different methods is a strong argument in favor of their being close to the true values.

In order to obtain the values of the table above, the author took the material presented in each of the published reports and reduced it to the same basis by a graphic method.

The table shows one reason for interchanging the letters A and B in the classification of spectra. There should also be added the temperatures of the O stars (15,000° to 22,000°) as determined by H. H. Plaskett.

The observed temperatures of the stars, however, are merely "effective" surface temperatures, for we receive heat and light only from the outer parts which can radiate into space. As with the sun, we must assume that if we could penetrate into the interior of a star we should find the temperature increasing with the depth, until at the center the temperature would be vastly higher than at the surface. From theoretical considerations Eddington deduced a value of 8,000,000° for the temperature at the center of a star of average mass and later investigations indicate even higher temperatures up to 20,000,000° or even 30,000,000°.

345. The Distances of the Stars.—It had been the dream of Sir William Herschel and of astronomers before him to determine the distances of some of the stars, but all their efforts were in vain. About 1838, however, Bessel at Königsberg, Struve at Dorpat and Henderson at the Cape of Good Hope succeeded in determining the distances of 61 Cygni, Vega and Alpha Centauri respectively.

The principle underlying the method employed by Bessel and Struve is still in use and will now be considered. From evidence to be given later (Sec. 357) we shall find that, on the average, the fainter stars are farther away than the brighter ones. As a consequence of the earth's revolution about the sun, a star which is comparatively near us would appear to change its position in the sky with reference to fainter and more distant stars. Thus, in Fig. 145, the star S would shift its position by the angle E_1SE_2 with respect to very distant stars lying in the same general direction, as the earth moved from E_1 to E_2 in the course of 6 months. This displacement would give the value of the angle E_1SE_2, and,

knowing the distance E_1E_2 to be 300,000,000 km, the distance from sun to star can be determined.

Bessel, Struve and their successors used an instrument called a *heliometer* for the measurement of the angular displacement of the star under consideration with respect to faint stars in the same field of view. The modern method consists in taking photographs of the star field at about 6-month intervals and measuring the displacement with respect to the faintest stars on the plate.

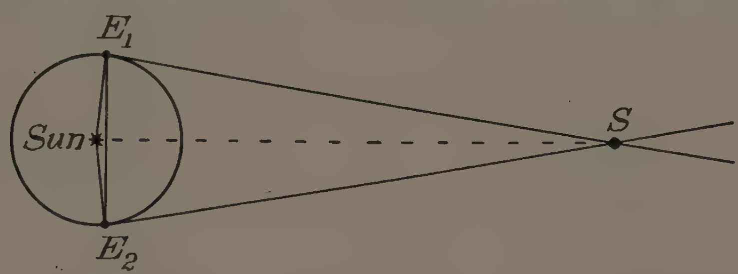


FIG. 145.—Determining the distance of a star by the trigonometric method.

346. Stellar Parallax.—In Fig. 145 the angle E_1S-*Sun*, the angle subtended at the star by the radius of the earth's orbit, is called the *parallax* of the star. The largest parallax known, $0''.76$, belongs to two stars, the double star Alpha Centauri and an eleventh magnitude star[1] about $2°.2$ distant from it. There is some evidence that the two stars are physically connected.

Parallaxes determined by the displacement method are called *trigonometric parallaxes.* It should be noted that these parallaxes are always relative to much fainter stars of unknown but presumably much greater distance. The parallaxes thus found are always too small by the amount of the mean parallax of the reference stars, but thus far no wholly satisfactory method has been devised to correct for this.

347. Units of Distance.—If a star were 206,265 times the sun's distance from us, its parallax would be exactly $1''$. This distance has come to be used as a unit of distance and has been given the name of *parsec.*

Another unit in common use is the *light-year*, the distance light travels in 1 year in a vacuum. One parsec is equal to 3.26 light-years.

348. Spectroscopic Parallaxes.—A careful study of the relative intensities of certain pairs of lines in the spectra of many stars

[1] This star was discovered by Innes at Johannesburg in 1915 and is sometimes called Proxima Centauri. It is one of the faintest stars known, having an absolute magnitude of about 15.5.

has shown that the relative intensity varies with the absolute magnitude (Sec. 356) of the star as determined from its apparent magnitude and trigonometric parallax. The relation thus established was so close that it is now being used with marked success as a measure of the absolute magnitude. Knowing also the apparent magnitude of the star its parallax follows.[1]

The spectroscopic parallax method was developed at the Mt. Wilson Observatory by Adams and Kohlschütter. It is now being used at several other observatories as well and is by far the most rapid method of parallax determination. Already several thousand parallaxes determined by this method have been published.

349. Other Methods of Determining Stellar Distances.—A number of other methods of determining the distances of stars have been developed, but for individual stars the two methods described are the best. Some of the others will be mentioned later.

350. Values of Stellar Distances.—A few of the largest stellar parallaxes are the following:

TABLE VIII

Star	Magnitude	Parallax	Distance, light-years
Alpha Centauri	0.2	0″.76	4.3
Proxima Centauri	11.0	0.76	4.3
Barnard's proper-motion star	9.5	0.54	6.0
Sirius	− 1.6	0.38	8.6
Procyon	0.5	0.31	10
61 Cygni	5.4	0.30	11
Altair	0.9	0.21	16

Most of the stars are very much farther away than these. There is evidence that some of the most distant stars may be as much as 1,000,000 light-years away.

351. Star Magnitudes.—In Ptolemy's Almagest the stars were divided into six groups according to their brightness. The brightest stars, like Sirius, Aldebaran and Altair, were called first-magnitude stars and the faintest stars seen with the naked eye were classed as of the sixth magnitude. Stars of intermediate

[1] The formula for this is $5 \log \pi = M - m - 5$, where π is the parallax, M the absolute magnitude and m the apparent magnitude of the star.

brightness were given as of the second, third, fourth and fifth magnitudes. Ptolemy's magnitudes were used for more than 1500 years.

The great revival of observational astronomy at the time of Sir William Herschel resulted in considerable confusion as regards star magnitudes, each observer having his own magnitude scale which adhered more or less closely to the general scheme of Ptolemy for naked-eye stars, but which became greatly confused when applied to telescopic stars. Various observers of the nineteenth century, among whom may be mentioned Heis and Argelander of Germany, Pogson and Pritchard of England and Gould of this country, helped to bring some order out of this chaos. The most important work, however, was done by Pickering of Harvard and the observers at Potsdam. By means of carefully made instruments and observations these two institutions established scales of magnitude of high precision. The Harvard scale is now almost universally used for visual work, and, with some necessary modifications, for photographic magnitudes as well.

352. Relation between Brightness and Magnitude.—Experiments on the part of several observers about the middle of the nineteenth century showed that the magnitude scale was not an arithmetical but a geometrical series of brightness. Observers had somewhat different values for the ratio of the brightness of one magnitude to the next but all were found to be using a ratio not far from 2.5. Pogson thereupon suggested that this ratio be taken as 2.512, so that a first-magnitude star would be precisely 100 times brighter than a sixth-magnitude star for $(2.512)^5 = 100$. This suggestion was adopted. Hence when we say that a certain star is one magnitude brighter than another we mean it is 2.512 times brighter, while if it is two magnitudes brighter it is $(2.512)^2$ times brighter, etc. This value of 2.512 is called the *magnitude ratio* or *light-ratio*.

353. Fractional Magnitudes.—Most stars do not fall at exactly whole magnitudes on the magnitude scale. It is therefore necessary to recognize fractional magnitudes as well. Thus, if a star looks to be half way between a second- and a third-magnitude star in brightness, it is said to be of magnitude 2.5. If somewhat nearer the second-magnitude star, it may be of magnitude 2.2 or 2.3, while if nearer the fainter star, it may be of magnitude 2.7 or 2.8. A tenth of a magnitude is a difference just perceptible to a trained observer. By means of visual photometers it is

possible to measure a difference of about one-tenth of a magnitude, while with the photoelectric photometer even one-hundredth of a magnitude difference can be determined.

In Table IX difference of magnitude and ratio of brightness are compared.

TABLE IX

Magnitude difference	Ratio of brightness	Magnitude difference	Ratio of brightness
0.5	1.6	4	39.8
1.0	2.5	5	100
1.5	4.0	10	10,000
2.0	6.3	15	1,000,000
3.0	15.8		

354. Negative Magnitudes.—On the Harvard scale Altair has a magnitude of 0.9, Aldebaran 1.1, Castor 2.0, Alpha Ursæ Majoris 2.0, Delta Ursæ Majoris 3.4. These stars may be used as standards for visual comparisons. There are, however, stars, such as Vega and Sirius, which are brighter than Altair. In order to have the magnitude scale continuous, it is necessary to recognize both zero and negative values. Thus Vega, which is 0.8 magnitude brighter than Altair, has a magnitude of 0.1, and Sirius, which is 2.5 magnitudes brighter than Altair, is of magnitude -1.6. Continuing the scale to still brighter objects, it is found that the sun has a magnitude of about -26.7.

355. Relation between Apparent Magnitude and Distance. According to a well-known law of physics, the brightness of a light varies inversely as the square of the distance. Thus, a light moved to double its original distance appears only one-fourth as bright, to five times the distance one-twenty-fifth as bright, to ten times the distance one one-hundredth as bright, etc. This law may be expressed by a simple formula,

$$I = 1/d^2,$$

where I is the intensity in terms of the brightness at unit distance and d the distance to which it may be removed. Solving the equation for d, we find $d = 1/\sqrt{I}$.

Let us now determine the necessary change in the distance of a star in order to decrease its brightness by one magnitude. Since the decrease of one magnitude makes the star only 1/2.512 times

as bright as before, we find $d = 1/\sqrt{1/2.512} = \sqrt{2.512} =$ 1.585 times the original distance.

To reduce its brightness two magnitudes it would have to be removed to $(1.585)^2$ times its original distance, and to reduce it five magnitudes it would have to be removed to $(1.585)^5 = 10$ times the distance. This last result may also be stated thus: To make a star appear five magnitudes fainter requires its removal to 10 times its original distance. At 10 times the distance it would be only one one-hundredth as bright, which agrees with the table of Sec. 353, which says that a star of any magnitude is 100 times as bright as one five magnitudes fainter.

356. Absolute Magnitude.—The apparent magnitudes of the stars vary from -1.6 for Sirius to about $+21$ for the faintest stars which have been photographed. The apparent magnitude of a star depends upon its intrinsic brightness and upon its distance. For many investigations a knowledge of the intrinsic brightness is of importance and the term *absolute magnitude* has been introduced to denote it. The absolute magnitude of a star is defined as its apparent magnitude if at a distance of 10 parsecs.[1] On this basis the absolute magnitude of the sun is $+4.7$ and a star of absolute magnitude -0.3 is $(2.512)^5 = 100$ times as bright as the sun, while one of absolute magnitude $+9.7$ would be only one one-hundredth as bright as our luminary.

Some stars are known of absolute magnitude exceeding -5, while others are as faint as absolute magnitude $+15$. This range in brightness represents intensities of the ratio 100,000,000 : 1.

357. The Luminosity Curve.—Kapteyn has worked out a table showing the relative proportions of stars of the various absolute magnitudes known between the values $+15$ and -5. The curve (Fig. 146) is drawn from the values given in his table. It is readily seen from the curve that 99 per cent of all the stars have absolute magnitudes ranging from $+15$ to 0 and that the average star is approximately of absolute magnitude $+7.7$. From the symmetry of the curve it is also seen that the number of stars fainter than the average is practically equal to the number brighter than this average. This leads us to two very important conclusions: (1) In dealing with any reasonably large number of

[1] Some writers use a distance of 1 parsec instead of 10. From the relation between magnitude and distance the absolute magnitudes on this basis are just five magnitudes brighter than on the other.

stars, say 10,000, in any average part of the sky, we can feel reasonably sure of the relative number of each absolute magnitude in the group; (2) if we are dealing with various groups of stars of the same apparent magnitude, the average distance of the various groups will be approximately the same, for in each group the number brighter than the average and therefore farther away will be approximately balanced by an equal number fainter than the average and therefore nearer.

Seares has recently found a good agreement with Kapteyn's curve on the side of the brighter stars, but marked disagreement on the other side. Ultimately, the luminosity curve may not prove to be as simple as shown in Fig. 146, but until a great increase in material can be obtained, the two conclusions reached may be accepted as a first approximation to the truth.

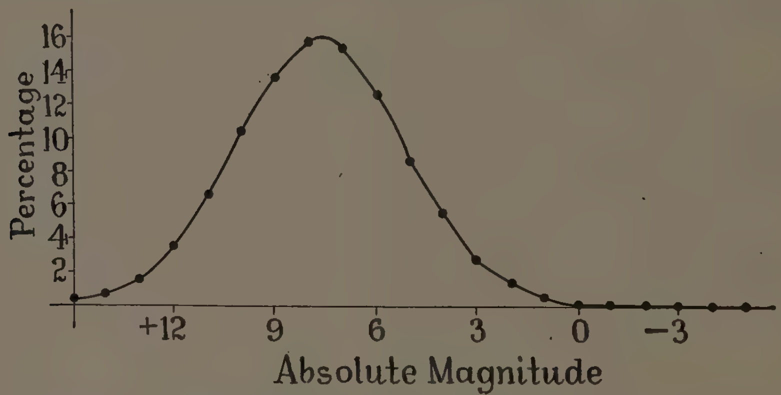


FIG. 146.—Kapteyn's luminosity curve, showing the percentage of the stars of various absolute magnitudes.

358. Total Number and Light of the Stars.—An investigation by Seares and van Rhijn shows that the total number of stars to the twenty-first magnitude is approximately one billion. They found no satisfactory way of determining the limiting magnitude of the stars nor their total number, but a theoretical investigation indicates the latter to be of the order of 3×10^{10}.

The same investigators also find that the total light of all the stars in the sky is equivalent to 1076 stars of magnitude 1.0. The uncertainty in the total number does not affect this value greatly, as the stars to magnitude 21 furnish 98 per cent of the total light.

359. Diameters of Stars.—For many years the only knowledge we had of the dimensions of stars, except the sun, was obtained from the eclipsing variable stars (Sec. 390). These binary systems gave values ranging from about 0.8 to 10 times the sun's diameter for the diameters of the components. Direct visual

observation of stellar diameters seemed forever hopeless, for the angular diameter of the spurious disc of a star in the great 254-cm (100-inch) telescope of the Mt. Wilson Observatory is between $0''.04$ and $0''.05$ and a star would have to show a disc nearly double this value to be certainly recognizable, and no star is near enough to do this.

The realization that there are giant stars had led Eddington, Russell and Wilsing to calculate the diameters of some of these from theoretical considerations. Their computed values for Betelgeuse were $0''.051$, $0''.031$ and $0''.039$ respectively.

Long ago Michelson had suggested a method of determining the diameters of Jupiter's satellites by interference methods and he had tried this as an experiment at the Lick Observatory in 1891. When the predictions mentioned above were made, Michelson believed it possible to try the same method on the stars. After some experimenting at the Yerkes Observatory he went to Mt. Wilson, and, with the help available there, an interferometer[1] 6 meters (20 feet) long was built to be used with the 254-cm telescope. In December, 1920, Pease of this observatory was successful in measuring the diameter of Betelgeuse. His result was $0''.046$, in remarkable agreement with the predicted values, considering the difficulties of the problem. Using the mean of the measured parallaxes for this star, the diameter becomes 344,000,000 km (215,000,000 miles). Since then the diameters of several other giant stars have been measured. These are given in Table X.

TABLE X

Star	Diameter (in millions)		Diameter (sun = 1)
	Kilometers	Miles	
Arcturus	34	21	24
Aldebaran	48	30	35
Scheat	240	150	175
Betelgeuse	344	215	250
Mira	400	250	290
Antares	640	400	460

[1] The theory of instrument and method is too complicated for this book. A simple explanation will be found in *Popular Astronomy*, vol. 29, p. 189, and a more elaborate one in the *Astrophysical Journal*, vol. 51, p. 257.

This great achievement naturally led to a desire to measure the diameters of other stars, but the difficulties in the way are very great. A larger instrument is being built at the Mt. Wilson Observatory for this purpose, and it is hoped that before long we shall know the actual diameters of many additional stars.

STELLAR MOTIONS

360. Radial Motions.—In the study of stellar spectra it is found that the star lines are usually displaced with reference to those of the comparison spectrum, either toward the red or toward the blue. According to the Doppler principle, this implies motion between the observer and the star in the line of sight. We know, of course, that the observer with his instrument is moving with the earth around the sun at an average velocity of 30 km (18.5 miles) per second. By allowing for the component of the earth's motion which is in the direction of the star (this is called the *reduction to the sun*), the remainder of the motion indicated by the displacement of the lines in the spectrum of the star represents the motion of the star with respect to the sun. This velocity in the line of sight is called *radial velocity* and is almost always referred to the sun.

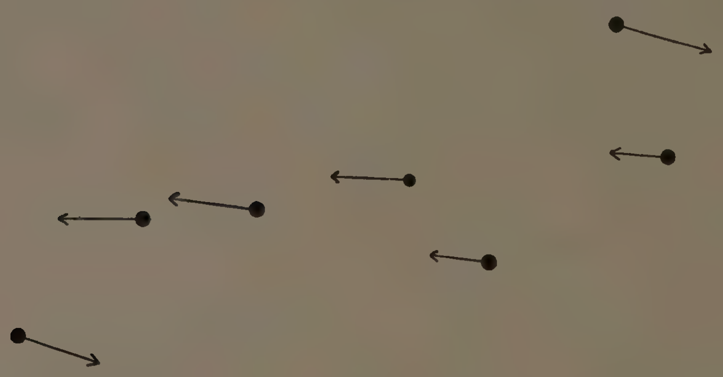


FIG. 147.—Proper motions of stars in Ursa Major. At the end of 100,000 years the stars will have moved to the points of the arrows.

Radial velocity is given a positive sign if the distance from the sun is increasing and a negative sign if the distance is decreasing. Radial velocities of stars from +339 km to −383 km (+211 to −240 miles) per second have been observed. The spectrograph, however, shows only that component of a star's real motion which is in the line of sight. It gives no information whatever concerning any crosswise component.

361. Proper Motion.—If we could again live on the earth 100,000 years hence and look toward that portion of the sky in

which we are now accustomed to see the Big Dipper, the well-known figure would be gone. Figure 147 shows it as it appears now, while 100,000 years hence the stars will occupy the positions of the heads of the arrows to which they are connected. Other stars would also be found to have changed their relative positions, but the little group of the Pleiades (Fig. 148) would still appear as it does now, for the stars of this group are moving together along practically parallel lines. This apparent relative motion of the stars among themselves, which is the component of the stars' motions across the line of sight, is called *proper motion*. Groups like the Pleiades are said to have common proper motion.

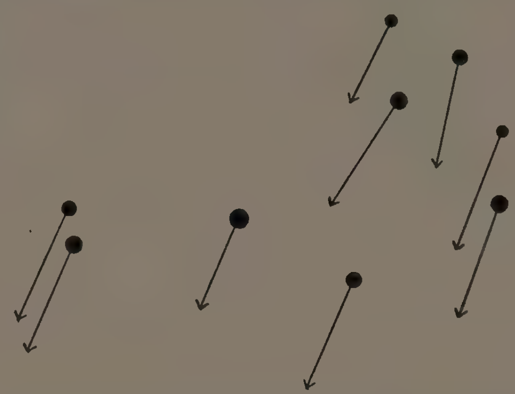


FIG. 148.—Proper motions of stars in the Pleiades. At the end of 20,000 years the stars will have moved to the points of the arrows.

362. Methods of Determining Proper Motion.—If we know the right ascension and declination of a star for two dates, such as 1850 and 1900, the two positions will not be the same because of precession, nutation, aberration and proper motion. By computing the corrections due to the first three and applying them to the position for 1850 we obtain the "1850 position reduced to 1900." The amount by which the reduced position differs from the observed position for 1900 will be the proper motion in the 50-year interval.

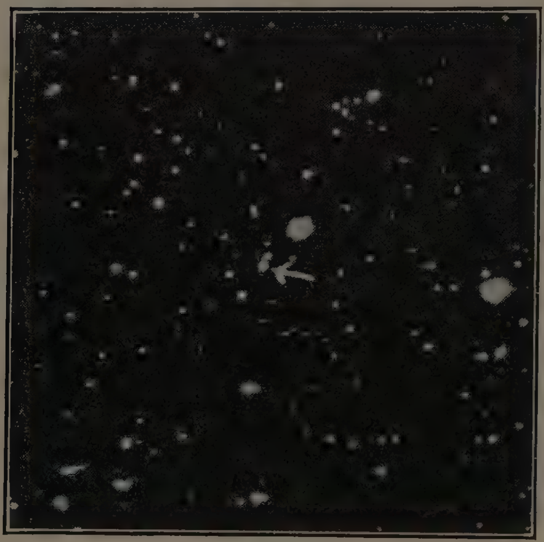
Another method of finding the larger proper motions is also available since celestial photography has become general. If we compare two plates taken of the same region with a considerable interval of time between them, it is possible to determine which stars have moved with respect to the entire group photographed (Fig. 149).

Proper motions of a few stars were discovered by Halley about two centuries ago and they have been the subject of investigation by many of the leading astronomers ever since. The proper motions of thousands of stars are now known with some degree of accuracy. The Dudley Observatory at Albany, N. Y., and the Yale, Greenwich and Cincinnati Observatories have made especially valuable contributions to our knowledge of proper motions. The Preliminary General Catalog of Boss of the Dud-

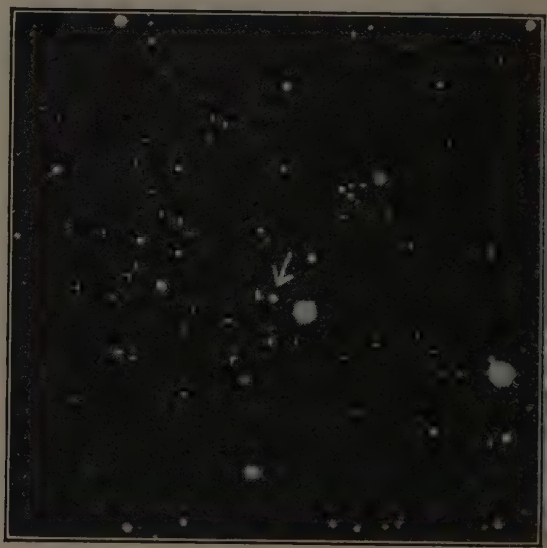
ley Observatory, which was published in 1910, is the standard proper-motion catalog at the present time.

363. Amount of Proper Motion.—Proper motion is usually expressed in seconds of arc per year or per century. For most of the stars it is exceedingly small. Only one star with a proper motion of more than 10″ per year is known (Fig. 149). It was discovered by Barnard at the Yerkes Observatory in 1916 in the constellation Ophiuchus. In this case the motion amounts to 10″.3 a year. The vast majority of stars showing any proper motion move less than 1″ a year.

In general, the brighter the star the greater its proper motion because the brighter stars as a class are nearer than the fainter ones and would therefore betray their motion most readily.



A



B

Fig. 149.—Barnard's proper-motion star: *A*, Aug. 24, 1894; *B*, May 30, 1916. (*Photographed at the Lick and Yerkes Observatories respectively.*)

If Newton's law of gravitation holds throughout the universe, then every star is subject to the gravitational attraction of every other. Since it is highly improbable that for any star the resultant of the attraction of all the stars should have been zero at the beginning, and continued so up to the present time, we would expect all stars to be moving more or less with respect to the others. Theoretically, therefore, stars, in general, should show some proper motion (and radial motion as well), but since most of them are very remote, the proper motions of only the nearer ones have been detected in the comparatively short time since accurate observations have been possible.

364. The Moving Cluster in Taurus.—In 1909, Lewis Boss announced the discovery of a group of stars in Taurus which had

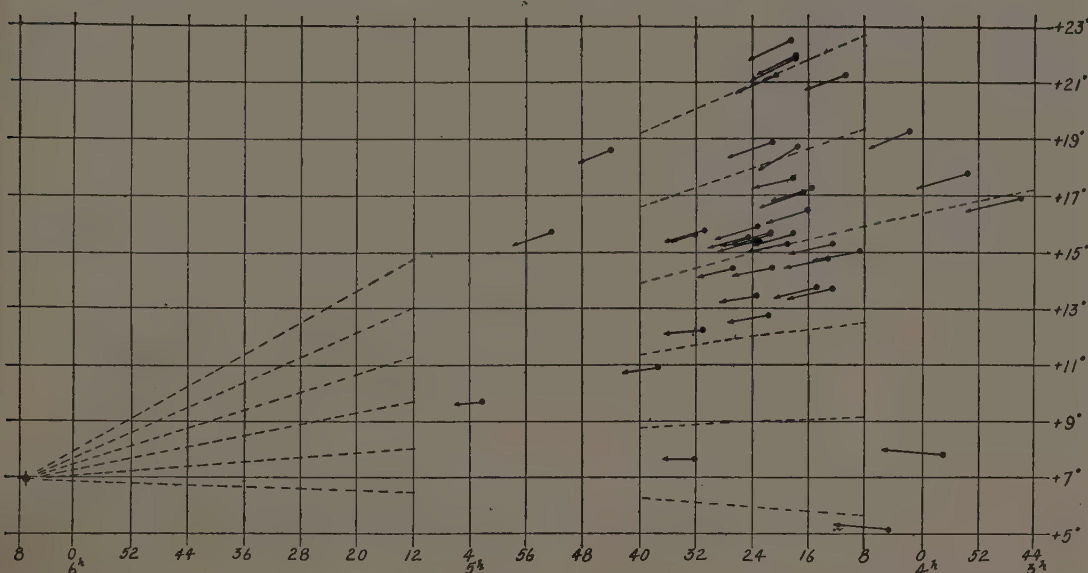


FIG. 150.—Moving cluster in Taurus. (*Courtesy of Astronomical Journal.*)

common proper motions. Figure 150 is a copy of his diagram. He found 39 stars distributed over an area about 15° square, whose proper motions, when projected forward, converged toward a single point in the sky. The explanation is that the stars are moving in parallel lines and the convergent is the vanishing point of the parallel lines.

In such a cluster there is a method of determining its distance if we can get the radial velocity of one or more of its stars. The method is as follows:

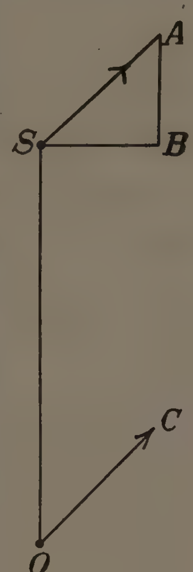


FIG. 151.—Method of determining the distance of a moving cluster of stars.

In Fig. 151 let O be the observer, who, for the sake of simplifying the problem, is assumed stationary in space, S the star of the group whose radial motion has been determined, SA the direction and amount of the star's motion in space and OC a line drawn to the convergent of the group. Since the convergent is the vanishing point for parallel lines, OC will be parallel to SA. Resolve the motion SA into two components, BA parallel to the line of sight and SB perpendicular to it. BA will give the radial velocity and SB will give the proper motion.

Since OC points toward the convergent and OS toward the star, we know the angle SOC. Assume it to be 45°. Then in

the triangle SAB the angle S is also 45° and AB is equal to SB. After determining the radial velocity, we know the velocity along SB will be equal to it.

Assume further that the proper motion in the direction SB amounts to 1″ a year. Then the distance SO will be 206,265 times the annual motion in the direction SB. By multiplying the observed radial velocity per second by the number of seconds in a year and this product by 206,265 we have the distance in kilometers.

If the right triangle SAB is not isosceles the relations of the sides can be determined by trigonometry, since the angle S is known. If the proper motion is other than 1″ a different factor must be used.

By a process analogous to this, and using more recent values for the radial velocities than Boss had available, H. C. Wilson finds the center of the Taurus cluster to be at a distance of 131 light-years and the diameter of the cluster to be 54 light-years. The luminosities of its stars vary from five to 100 times the luminosity of the sun.

A number of clusters of a similar character are known.

365. The Sun's Motion.—Since our sun is one of the stars, we would expect it to be in motion like the others. If we are in a grove of trees and move toward some part of the grove, the trees in that direction appear to be moving apart, those on either side to move in a direction opposite to our own and those behind us to move closer together.

In a similar manner the analysis of the proper motions of the stars has shown that in one part of the sky their general tendency is to move toward each other, in the opposite part of the sky to separate, while in the region between they appear to be streaming past. The simplest explanation of this phenomenon is that the sun is moving toward that part of the heavens where the stars are separating. From the investigations of Lewis Boss on the proper motions of over 5000 stars, the sun is moving toward a point in the sky whose position is R. A. = $18^h\ 2^m$, Dec. = $+34°.3$, not far from the bright star Vega.

Let us return to the illustration of the grove of trees. The trees toward which we are moving would be approaching us, those behind would be receding, while those on the sides would be neither approaching nor receding. An investigation by Campbell of the Lick Observatory on the radial velocities of over 2000 stars

shows precisely this general effect. In one part of the sky the stars on the whole are approaching, in the opposite part they are receding, while in the region between they are, on the average, doing neither. The point toward which the sun is moving as determined by Campbell is in R. A = $17^h\ 56^m$, Dec. = $+27°.2$, in good agreement with the position determined by Boss from the proper motions.

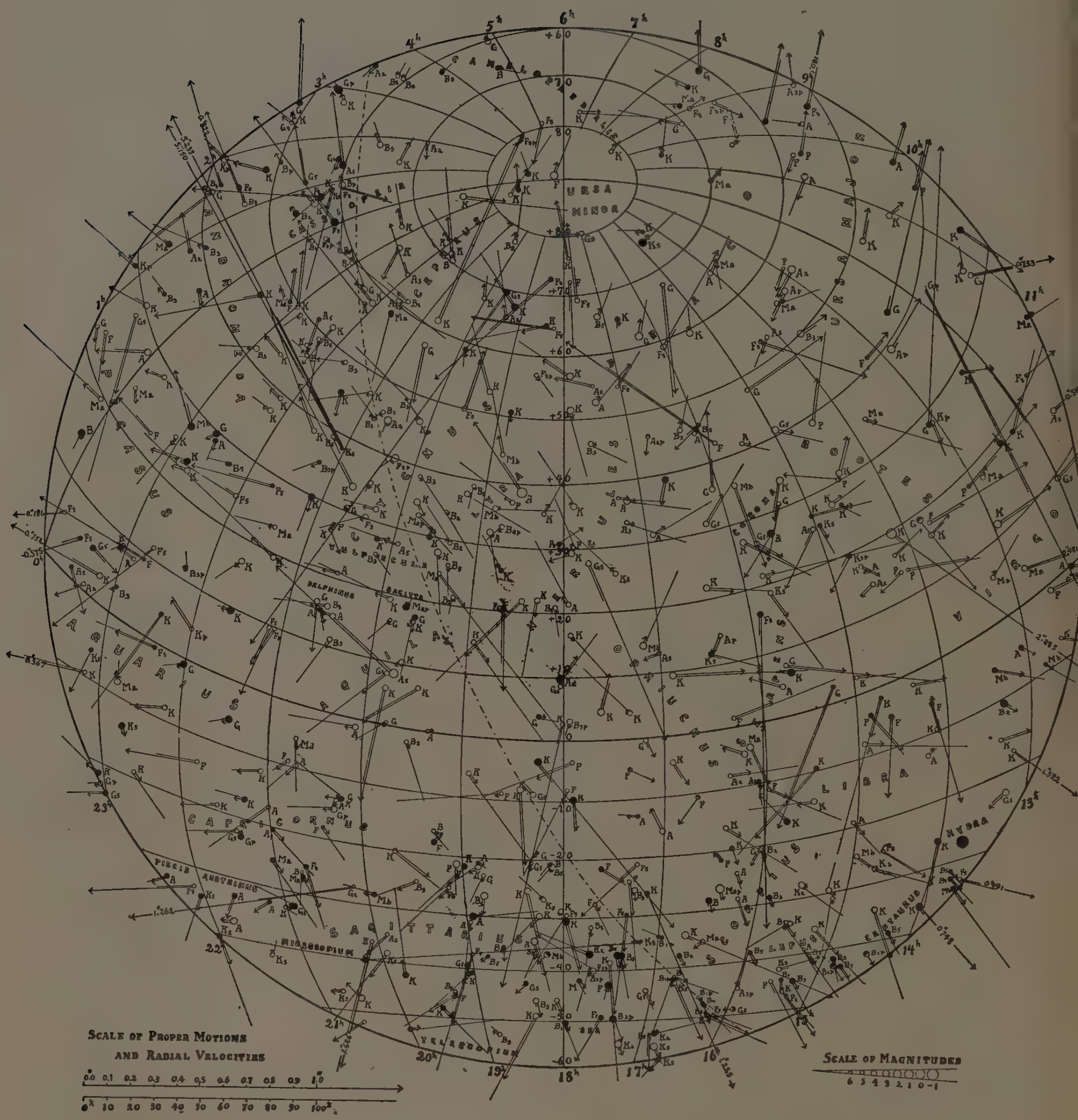
The sun's motion through space is called the *sun's way* and the point toward which it is moving is termed the *apex of the sun's way*. The velocity of the sun's motion as determined by Campbell is 19.0 km (12 miles) per second.

366. Proper-motion and Radial-velocity Figures.—Figures 152 and 153 illustrate the determination of the apex of the sun's way from the proper motions and radial velocities of 1157 stars. The drawings were made by Prof. H. C. Wilson, who very kindly permitted their reproduction here.

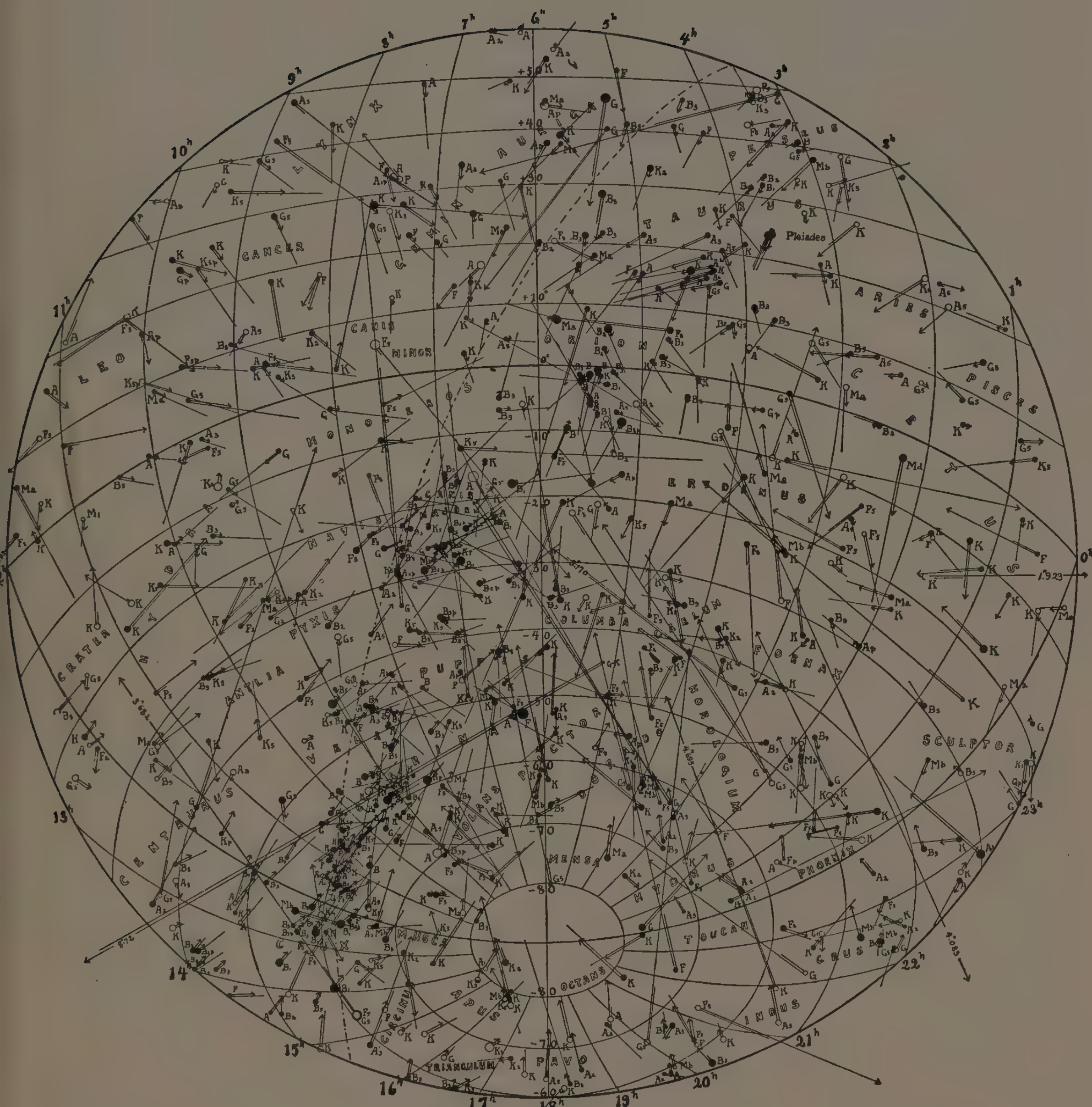
The figures represent the two hemispheres of the celestial sphere whose centers are at R. A. 18^h, Dec. $+30°$, and R. A. 6^h, Dec. $-30°$, respectively. Proper motions of the stars are indicated by arrows attached, the direction of the proper motion being indicated by the direction of the arrow, and the amount of the proper motion in 125,000 years by the length of the arrow. Radial motions are indicated in amount by a line drawn parallel to the proper-motion arrow. If the distance between star and sun is diminishing, the star is represented by an open circle, while if it is increasing, this is shown by a filled circle.

Inspection of the figures shows that, on the whole, the proper motions diverge from the center of Fig. 152 and converge toward the center of Fig. 153. Where the proper motions are divergent, the stars, in general, are approaching the sun, and where the proper motions are convergent, the stars are receding. Near the boundaries of the two figures both the proper motions and radial velocities show little or no regularity, as might be expected. The figures illustrate clearly the evidence for the sun's motion with respect to the stars.

367. Parallactic and Peculiar Motions.—Since the sun is moving among the stars, it is evident that a part of the proper motion as observed must be caused by the sun's motion. We must therefore separate the component due to the sun from the observed proper motions in order to study the motions of the stars among themselves. That component of the proper motion



FIGS. 152 and 153.—Apex of the sun's way as shown by proper motions a
motions and their relative amounts. Open circles indicate negative rad
(*Drawings by H. C. Wilson of the Goodsell Observatory from data available at*



dial velocities of 1157 stars. The arrows indicate the direction of the proper
elocities (stars approaching observer) and filled circles positive radial velocities.
ck Observatory in 1911.)

which results from the sun's motion is called the *parallactic motion* and the component which represents the star's own motion is called its *peculiar motion.*

368. Radial Motions and Spectral Class.—Campbell has recently announced the results of his many years' observations of stellar radial velocities. After subtracting the effect of the solar motion from the observed radial velocities of over 2000 stars he finds a most interesting relationship existing between these velocities and the spectral type of the stars. This result in tabular form is as follows:

TABLE XI

Spectral class	Number of stars	Average radial velocity, kilometers per second
B0–B5	243	7.4
B8–A3	441	9.6
A5–F2	195	12.5
F5–G0	242	15.8
G5–K2	680	15.5
K5–Mb	232	16.7

There is no very satisfactory explanation for this change in velocity with spectral type but we shall refer to it again in the next section.

369. Proper Motions and Spectral Class.—On the basis of the material in the Preliminary General Catalog, after excluding all stars having proper motions exceeding 20″ per century, Boss published a table showing the relation between proper motions and spectral class. This table in abridged form is as follows:

TABLE XII

Spectral class	Number of stars	Average proper motion per century
O and B	707	2″.8
A	1,552	5.0
F	492	7.9
G	444	5.2
K	1,227	5.7
M	222	5.0

The explanation of this relationship is likewise not clear. There is evidence that the average stars of the O and B types are farther away than the average of the others, and this greater distance would, in general, result in smaller proper motions but even this does not seem to be the complete explanation. Boss was led to conclude that even when allowing for distance there is still evidence that, on the whole, the relative velocities of the groups O-B, A and F-M are in the ratio of 6.3:10.2:16.6. This is in general agreement with the results obtained from the radial velocities as given in the preceding section, so that there is good reason to believe we are dealing with one of the fundamental facts of stellar motion. According to Russell's theory of stellar evolution (Sec. 451), the B stars are more massive than the average of the other spectral types, so that we may assume the following to be a statement which is in accord with fact: *The more massive stars have smaller velocities than the less massive.* We need additional facts before we shall have an adequate explanation.

370. Solar Motion and Stellar Magnitude.—A number of investigations have been made which show that both the direction and the amount of the sun's motion depend upon the magnitudes of the stars involved as well as on their spectral class. Thus Stromberg has shown that with reference to 800 stars of absolute magnitude averaging zero the sun's velocity is 19 km per second, while with reference to 415 stars of about +4.6 absolute magnitude the velocity is nearly 32 km per second. The stars used were of spectral types ranging from F to M.

The position of the apex of the sun's way also changes as stars of various spectral types are used. A great deal of new material is being published from time to time, but no definitive statement can be made concerning its bearing on the sun's motion or on the larger question of the structure of the stellar system. Enough has been said, however, to show something of the complexity of the problem and some of the factors which have to be considered.

371. Star Drifts.—In 1904, Kapteyn announced the results of a study of the proper motions of 2400 stars. After eliminating the parallactic motion the peculiar motions showed a decided tendency to separate themselves into two groups, the one group indicating motion toward a point in R. A. $6^h\ 4^m$, Dec. +13°, and the other a motion toward R. A. $18^h\ 4^m$, Dec. −13°. This distribution of peculiar motions was explained by Kap-

teyn as due to two groups of stars moving through each other in opposite directions. He referred to these as two star "streams," but the term star "drifts," suggested by Eddington, is now more generally used. The relative velocity of the two drifts is about 40 km (25 miles) per second.

The two points toward which the star drifts are moving both lie in the Milky Way. These two points are called the *vertices* of the corresponding drifts.

There is also some evidence of the existence of a third group of stars practically at rest with respect to the two drifts. This third group is usually called Drift O. The other two drifts are referred to as Drifts A and B. Drifts A and B contain stars of spectral types A to M, but no B-type stars. Drift O, however, contains all the B-type stars as well as some others. The B-type stars thus seem to be a special group.

The motions of the stars in any drift are not along parallel lines as in the Taurus group. There is considerable variation both in the direction and in the velocity of the individual stars, but when the group is taken as a whole it shows a decided group motion toward its vertex.

The work on star drifts depends on proper motions. Since we know the proper motions of relatively near stars only we must not assume that distant stars will have the same vertices as Drifts A and B.

Work by Schwarzschild, Stromberg and others casts some doubt on the simple physical explanation of two drifts as given by Kapteyn, but more material is necessary before a reasonably complete discussion of the space velocities of the stars and their relationships can be made. In the meantime we can accept Kapteyn's work as a first approximation which may be modified when we have more nearly complete knowledge of the factors involved in the problem.

CHAPTER XVI

THE STARS (*Continued*)

372. Double and Multiple Stars.—There are in the sky a number of stars which appear single to the ordinary eye but which may be separated into two components by a keen eye. A good example of such a star is ϵ Lyræ. When the telescope is used, many thousands of close pairs are found.

In some cases the two components are of approximately the same brightness, while in others there is a difference of many magnitudes. An example of the first kind is γ Virginis, with components of magnitude 3.6 and 3.7, while one of the second kind is Sirius, with components of magnitude -1.6 and 8.5.

Occasionally, a star is found which on examination proves to have more than two components. Such stars are called *multiple stars*. An example of this is θ Orionis, in which four stars can be detected with a telescope of ordinary size.

373. Optical and Physical Double Stars.—Some double stars are such only because two stars are seen nearly in line, whereas, in reality, they are far apart in space and have no physical connection. Such a pair is called an *optical double star*. Stars of this kind will, in general, ultimately betray their true character because their proper motions will finally separate them.

Other double stars are not only apparently but actually close together, bound to one another by their mutual gravitation. They show this connection either by having a common proper motion or by showing orbital motion around their center of mass. Such pairs are called *physical double stars*. Stars which show orbital motion are known as *binary stars*.

374. Binary Stars.—The first binary stars were discovered by Sir William Herschel. In 1781 he had presented before the Royal Society a paper "On the Parallaxes of the Fixed Stars," in which he called attention to the value of the displacement method (trigonometric) in parallaxes and stated that very close double stars offered the greatest promise of success. (At this time he seems to have assumed them to be optical doubles only.)

The next year he presented a catalog of 269 double stars, and a second list of 434 additional ones followed two years later. He failed to find the parallaxes he sought, but in 1797 he began remeasuring his double stars and by 1803 he was able to present evidence that "many of them are not merely double in appearance, but must be allowed to be real binary combinations of two stars, intimately held together by the bonds of mutual attraction."

375. Designation of Double Stars.—While practically all stars which occur in the lists of double stars have their customary constellation letter or catalog number, it has nevertheless been found convenient to designate them by a letter and number, the letter signifying the discoverer and the number the order in which the star stands in his list of discoveries. Thus Σ 554 means the star ordinarily known as 80 Tauri, but which is No. 554 in F.G.W. Struve's Catalogus Novus and in his famous Mensuræ Micrometricæ; β 491 is δ Andromedæ and is No. 491 in Burnham's list of discoveries, while A 2900 similarly represents Aitken's twenty-nine-hundredth discovery.

Burnham made a complete list of all known double stars, including a record of the measurements. This was published in two volumes by the Carnegie Institution in 1906 and contains the data for 13,665 stars. A convenient designation is the number of the star in this General Catalog of Burnham.

376. Measurement of Double Stars.—The measurement of a double star has for its purpose the determination of the position of one component, called the *companion*, with respect to the other, called the *primary*. When the stars are of unequal magnitude the brighter is termed the primary, but when they are equal in magnitude one must be selected arbitrarily as the primary.

The two quantities that it is possible to measure are the direction of the line joining the two stars and the angular distance between them. This measurement is accomplished by means of the micrometer attached to the telescope which is usually provided with but two parallel spider threads, one fixed and the other movable by means of a fine screw. After the direction of the north-and-south line in the field has been determined and the circle reading obtained, the threads are placed parallel to the line joining the stars and the circle read again. The difference in the circle readings gives the angle which the line joining the primary to the companion makes with the north-and-south line through the primary. This angle is called the *position-angle* and is meas-

ured around the circle from the north through the east. In Fig. 154 the position-angle is about 135°. The micrometer is then rotated 90° and the angular separation of the two stars measured by means of the micrometer threads. This angular separation is called *distance*. Figure 155 shows the change in position-angle in the faint companion of the star known as Krueger 60.

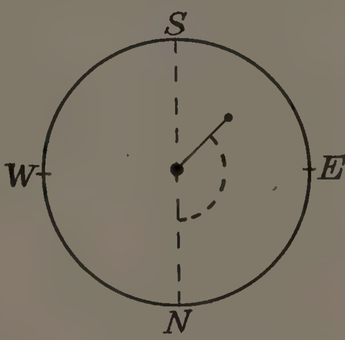
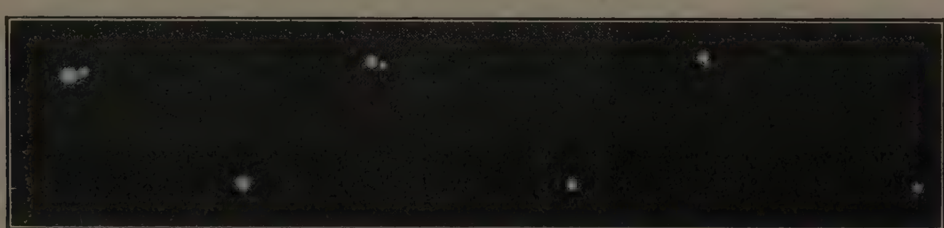


FIG. 154.—Position-angle of a double star.

377. The Orbit of a Visual Binary.—If a series of measures of position-angle and distance have been made covering one complete revolution of the stars around their center of mass, it is possible to plot the apparent orbit of the one about the other. For a well-observed pair this is always an ellipse, but unless the orbit plane makes an angle of 90° with the line of sight it is not the true orbit. It is then the work of the computer to determine the real orbit of the one with respect to the other. Figure 156 shows the apparent orbit of the companion of Sirius.

The point of the orbit nearest the primary is termed *periastron* and the opposite point *apastron*.



A B C

FIG. 155.—Change in position-angle of faint companion of the star Krueger 60. *A*, 1908; *B*, 1915; *C*, 1920. (*Photographed at the Yerkes Observatory.*)

The periods of visual binary stars vary from 5.70 years for δ Equulei to many thousands but, since those of long period have not completed an entire revolution, definite values cannot be obtained.

The lengths of the semi-major axes of visual binary star orbits listed in Aitken's book vary from $0''.16$ for β 524 to $17''.65$ for α Centauri.

The eccentricities vary from 0.134 for Σ 518 to 0.96 for Σ 1865.

378. Colors of Double Stars.—When there is but little difference in brightness in the components of a double star, they are generally of the same color but when there is a considerable

difference in brightness, the color of the fainter star is usually bluer. This peculiarity has been demonstrated to be largely a subjective effect, and, judging from the varying descriptions of the colors by different observers, is also dependent upon peculiarities of vision of some observers.

379. Number and Distribution of Double Stars.—There are many double stars still undiscovered, but the Lick Observatory survey by Aitken and Hussey is an extraordinarily valuable piece of observational work. This survey involved a careful scrutiny of all stars of magnitude 9.0 or brighter listed in the B. D. from the north celestial pole to −22° declination to see if

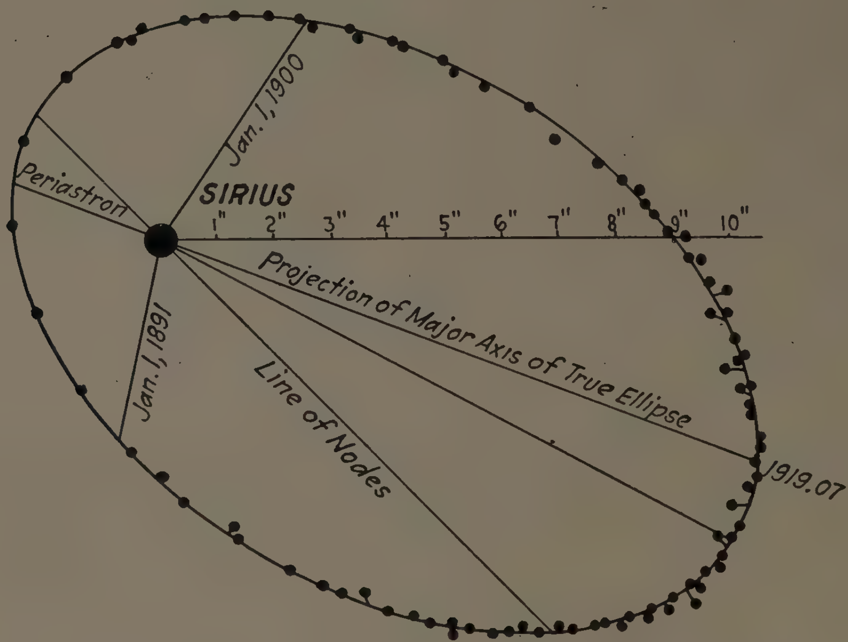


Fig. 156.—Apparent orbit of the companion of Sirius around its primary. (*According to Howard in Popular Astronomy*, 1922.)

they were single or double. In his book on Binary Stars, Aitken has given the results of the work for the northern hemisphere of the sky. A total of 100,979 stars was involved, and of these 5400 were double stars. The discoveries were as follows: W. Struve 1053, O. Struve 296, Burnham 551, Hough 237, Hussey 766, Aitken 2057, all others 440. We thus see that about one star in every 18 as bright as 9.0 in the northern sky is a double star as seen with the 36-inch Lick refractor.

Another result obtained was that the proportion of double stars in or near the Milky Way is slightly greater than at a distance from it.

There seems to be no reason for believing that when similar information is available for the southern hemisphere the proportions will be changed materially.

380. Spectroscopic Binary Stars.—In 1889, E. C. Pickering announced that the star Mizar, ζ Ursæ Majoris, showed a very

Fig. 157.—Portion of spectrum of ζ Ursæ Majoris (Mizar) showing single lines (above) and double lines (below). (*Photographed at the Yerkes Observatory.*)

peculiar spectrum in that at times the lines appeared double, at other times single and at other times they were merely broadened (Fig. 157). His explanation was that the star really consisted of two components of the same spectral type and of approximately equal brightness which are revolving around their common center

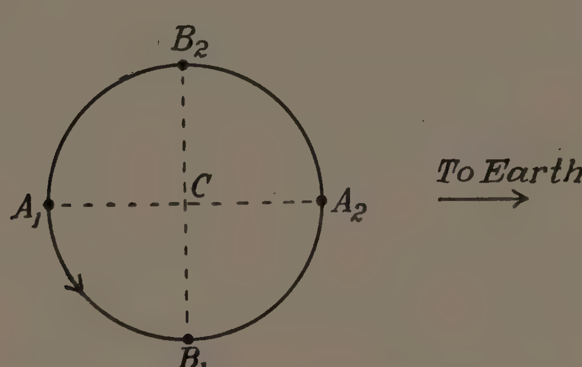


Fig. 158.—Explanation of single and double lines in spectrum of Mizar.

of mass. When the stars are in the positions A_1, A_2 (Fig. 158), they are moving across the line of sight and the light from the two would show single lines. When they are in the positions B_1, B_2, however, the lines in the spectrum of B_2 would be shifted toward the red while those of B_1 would be shifted toward the

violet and the lines of the combined spectrum would be double, one set belonging to star 1 and the other to star 2. The period of revolution of the two stars is about 20.5 days. A star of this kind is called a *spectroscopic binary star*. If the plane of the orbit also passes very near the earth, it will also be an eclipsing variable star (Sec. 390).

381. Variable Radial-velocity Stars.—If the components of a spectroscopic binary star are of about equal magnitude, both spectra will be visible, but when there is a difference of several magnitudes, the spectrum of the brighter one alone is visible on the photographic plate. Since the spectra are superposed on the plate, no increase of exposure will bring out the fainter spectrum.

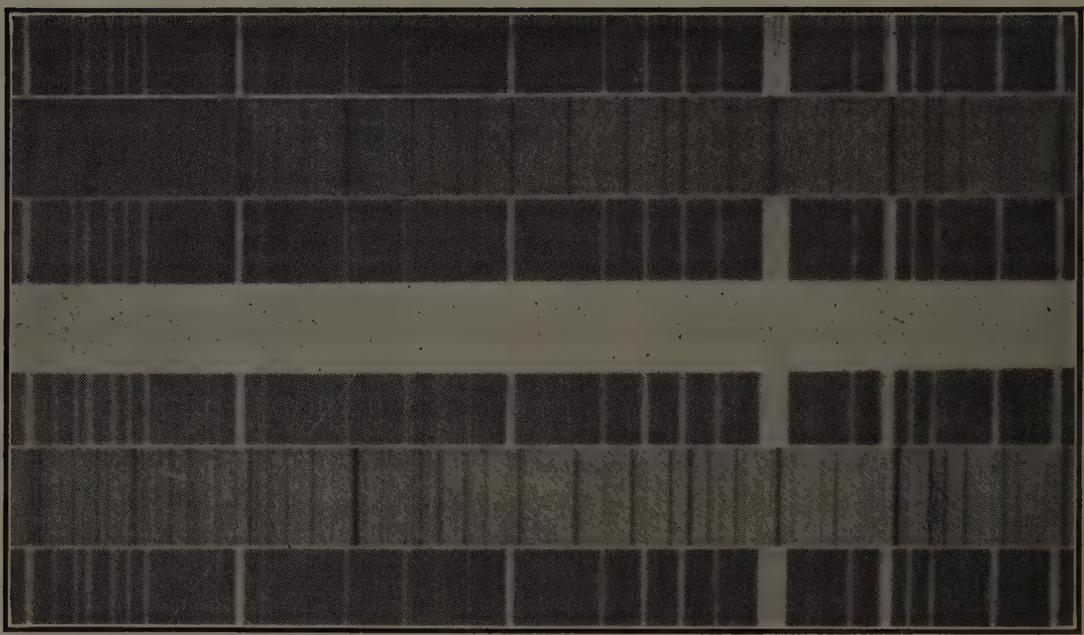


Fig. 159.—Shifting of the position of the lines in the spectrum of μ Orionis due to change in radial velocity. (*Photographed at the Yerkes Observatory.*)

When the spectrum of only one component of a spectroscopic binary is visible, the binary character is shown by the shifting of the lines (Fig. 159) of the spectrum—toward the red when this component is moving away from and toward the violet when moving toward the earth. In such a case a series of spectrograms will give values of the radial velocity which show definite periods corresponding to the period of revolution of the binary. When these values[1] are plotted with reference to the period, a curve, known as the velocity curve, is formed. Figure 160 shows the velocity curve of μ Orionis as determined at the Yerkes Observa-

[1] After reduction to the sun.

tory. From this curve the computer can determine the elements of the orbit. These elements are the radial velocity of the center of mass of the binary, the period, the eccentricity of the orbit, the half-amplitude of the velocity curve, the angle between the line of nodes and the line from the center of mass to periastron, the time of some periastron passage and the length of the semi-major axis of the true orbit multiplied by the sine of the angle between the plane of the orbit and a plane perpendicular to the line of sight.

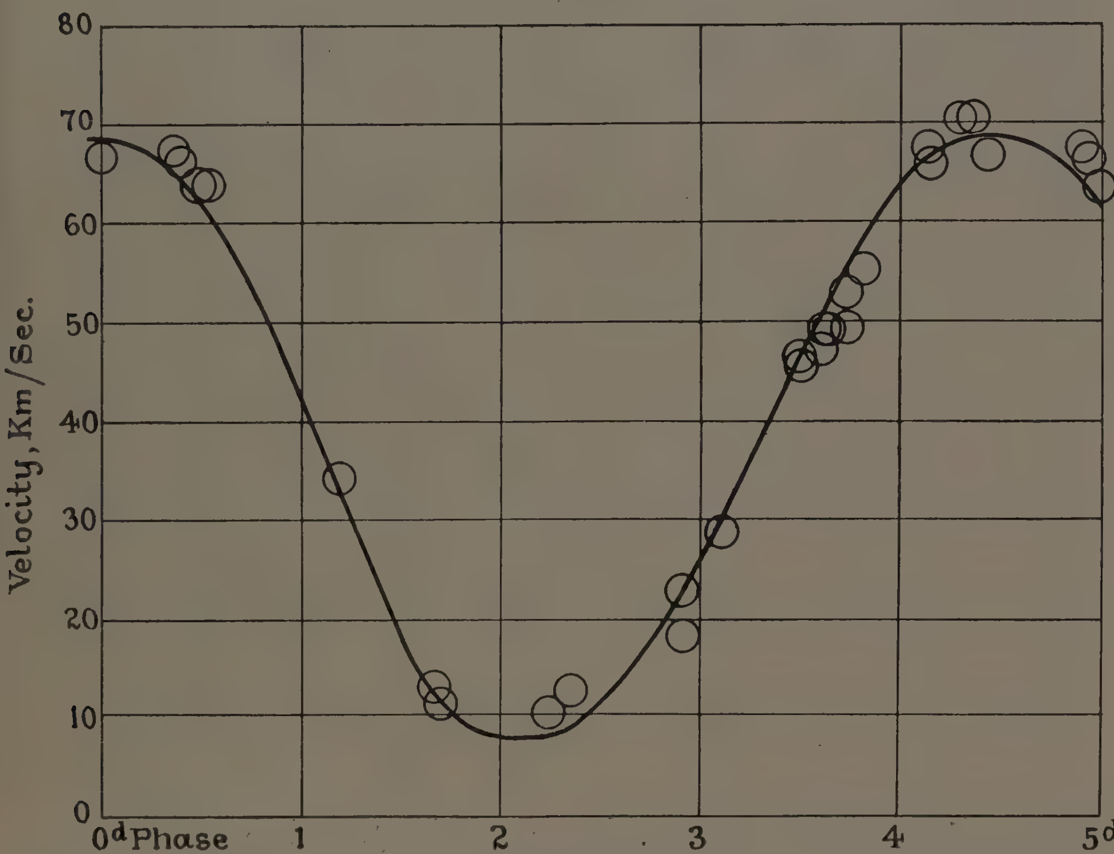


FIG. 160.—Velocity curve of μ Orionis as determined at the Yerkes Observatory.

The range in velocity as shown by the velocity curve is often great. In the case of δ Pictoris this amounts to 342 km.

When both spectra are visible it is possible to determine the orbit of one component with respect to the other, as in a visual binary. Their relative masses may also be obtained as well as minimum values of the masses. For TT Aurigæ, Adams and Joy have found a relative velocity of the two components amounting to 450 km per second.

382. Catalog of Spectroscopic Binary Stars.—The Lick Observatory has recently issued the Third Catalog of Spectro-

scopic Binary Stars which gives data to July 1, 1924. There are listed 1054 stars of variable radial velocity including 42 stars known as Cepheid variables. As we shall see later (Sec. 388), it is probable that stars of this class are not binaries but there is strong presumption that the other 1012 are true binaries.

It is evident that every visual binary star whose orbit plane is not accurately perpendicular to the line of sight is a potential spectroscopic binary star.

The orbits of about 250 spectroscopic binary stars have been computed. Their periods range from about 2.5 hours for γ Ursæ Minoris to many years in some cases.

VARIABLE STARS

A variable star is one whose brightness changes from time to time. The usual method of illustrating the change is to draw a graph in which the varying magnitude of the star is plotted as one coordinate and time as the other.

383. Designation of Variables.—In accordance with a suggestion by Argelander, the first variable star discovered in a constellation was called R followed by the name of the constellation, the second by S, etc., to Z. When the single letters were exhausted two letters were used beginning at RR, RS, etc., then SS, ST, etc. In some cases even this has not provided sufficient combinations, so that recourse was taken to the first letters AA, AB, etc. In some cases, when a star has been known by some particular name, such as Algol or δ Cephei, and later proved to be variable the original name was kept. Several other classifications are also in limited use, but there is need of a thorough revision of the entire scheme.

In the case of the temporary stars, also called new stars, the Latin word *nova* followed by the constellation is used. If a second is discovered in the same constellation it becomes No. 2, etc.; *e.g.*, the temporary star found in Aquila in June, 1918, is known as Nova Aquilæ No. 3, because two others of the same kind had been known before in that constellation.

384. Classification.—No really satisfactory scheme of classification of variable stars has been devised because, with few exceptions, we do not know the causes underlying the variation. The following plan, which is in general use, serves to point out the main types of variation but it can lay no claim to be anything more than provisional:

Class I. Temporary stars.
Class II. Variable stars of long period.
Class III. Irregular variables.
Class IV. Cepheid variables.
Class V. Eclipsing variables.

385. Class I—Temporary Stars.—This group is the most spectacular of all variables. An example will illustrate.

On the night of June 7 to 8, 1918, a new star of the first magnitude was noted in the constellation Aquila. By the next night its magnitude rose to -1.2. Thereafter it slowly waned, being of magnitude 4 by the end of June and of magnitude 6 by the middle of November. From the last of June on it fluctuated more or less, with some evidence of a 12-day period. The fluctuations continued but the star gradually became fainter, until in October, 1921, it had reached the tenth magnitude. In the meantime a search of photographs of that region of the sky taken before the outburst showed that the star had been for some time of about magnitude 10.5 and was still that faint on the night of June 5. Between this date and June 9 it rose from magnitude 10.5 to -1.2, a difference of nearly 12 magnitudes, which meant an increase in brightness of about 60,000 fold. Some extraordinary thing must have occurred to cause such an outburst in so short a time.

About 40 stars of this class have been observed since 1572 and all but five of these in the last 100 years. All show the same rapid rise to a maximum and then a less rapid decline, usually with fluctuations of a more or less periodic character. These stars are often called new stars or novæ. The latter name, used in this technical sense, is not objectionable, but the use of the word "new" seems to imply a star not previously existing and therefore should not be used, as the evidence seems clear that the phenomenon is a great outburst of a faint star.

The spectra of novæ are more or less alike. If caught before reaching maximum brightness there is a strong continuous spectrum with a few absorption lines, so that it appears to be somewhat like that of a B- or A-type star. At maximum brightness and for a few days thereafter strong bright bands of hydrogen and other elements appear, together with absorption lines corresponding, the latter being displaced to the violet. These displacements correspond to a motion up to 2000 km per second. Then more complicated changes occur until after a time the spectrum

resembles that of a planetary nebula (Sec. 414). After a lapse of several years the spectrum gradually changes until it is that of an O-type star. So far as known, this is the last stage of the nova spectrum.

No really satisfactory theory has been advanced to account for novæ. Some hold to a collision theory, either of two stars or of a star and a possible planet, while others believe the star moves into a region filled with finely dispersed material, so that the phenomenon resembles a shooting star on a cosmic scale. None of these theories appear to be entirely adequate. Another view is that the causes probably lie within the star itself, but no satisfactory reason is given for the outburst.

All novæ of our stellar system have appeared in or near the Milky Way. Any adequate theory must account for this peculiar distribution.

386. Class II—Variable Stars of Long Period.—The name itself gives one of the characteristics, namely, that the variation goes through a more or less regular cycle and then repeats. The periods range from about 50 to over 600 days, but most of them lie between 250 and 300 days. This group contains most of the variable stars known at this time. In general, they are reddish stars and have M-type spectra.

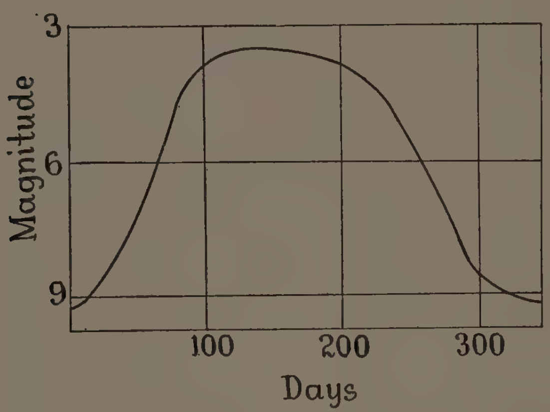


FIG. 161.—Average light-curve of *o* Ceti.

A typical star of this class is *o* Ceti, sometimes called Mira, the wonderful, the first variable discovered. In August, 1596, an amateur astronomer, D. Fabricius, saw in the constellation Cetus a second-magnitude star which he had never seen before. It soon faded from view. He saw it again for a few weeks beginning in February, 1609, but does not appear to have given it much further attention. In 1638 it was independently discovered by Holwarda, and later seen by others. Hevelius followed it with sufficient energy to detect its variability in the interval 1648 to 1662.

During most of the time the star is below naked-eye visibility, but about every 11 months it is visible for some weeks. At maximum it may almost reach the second magnitude but some-

times it rises only to the fifth. The time between successive maxima is not constant but averages approximately 11 months. At minimum it sinks to about the ninth magnitude. The rise to maximum is more rapid than the decline and there are some fluctuations throughout. Figure 161 is an average light-curve.

There have recently been published the results of work at the Mt. Wilson Observatory which assign to this star the enormous diameter of 400,000,000 km (250,000,000 miles), the second largest known. Whether the other variable stars of this class will also prove to be such giants is not known at present.

387. Class III—Irregular Variable Stars.—This group contains all stars whose light is known to vary and which cannot be included in the other groups. In some cases, such as α Orionis or α Herculis, we merely know that their light is not constant, but absolutely no regularity seems discoverable in the variation. In other cases, such as SS Cygni, the star is ordinarily faint but

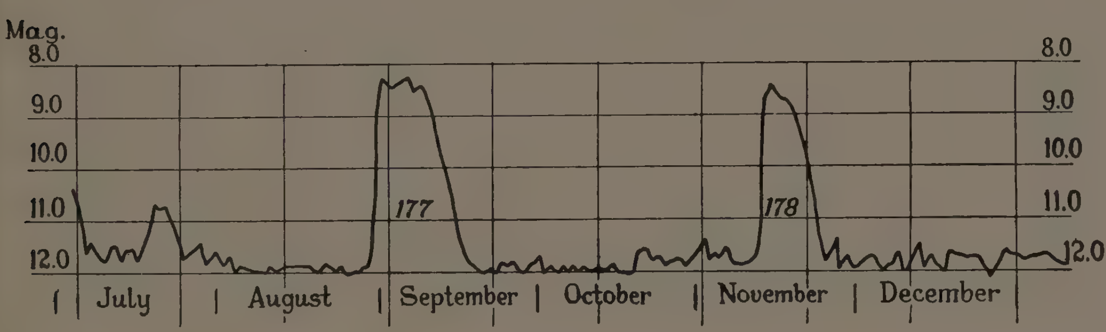


Fig. 162.—Portion of light-curve of SS Cygni in 1920 according to H. O. Eaton, from observations of American Association of Variable Star Observers. (*From Popular Astronomy.*)

suddenly rises two or three magnitudes in brightness and then falls again. The maxima come more or less irregularly and may show some similarity or not. Figure 162 shows two types of maxima of SS Cygni as derived by H. O. Eaton.

Another star of this class is R Coronæ Borealis. It may remain for years at about the sixth magnitude and then suddenly fade away in a few weeks to the tenth or twelfth magnitude or even to the fifteenth. After some fluctuations, which may last for some years, it again returns to the sixth magnitude.

The causes underlying the variation of stars of this class are unknown. Some suggestions which have been made are as follows:

Stars like α Orionis may develop many spots like sun-spots. When the spots are very numerous and cover appreciable portions of the star's surface, they may cut off sufficient light to cause the variations observed. This suggestion, however, involves the assumption that there is no spot period as for the sun.

Stars like R Coronæ Borealis may be assumed to pass through masses of nebulous matter in their journeys through space. When passing into or behind a cloud of nebulous material the light is diminished, the amount of diminution depending upon the amount of light absorbed by the nebulosity. After the star passes out of the nebulous region it regains its normal brightness.

388. Class IV—The Cepheid Variables.—This group takes its name from the first one discovered, δ Cephei. All are known to be giant suns, much larger than our own. Their periods vary from less than one day to about 100 days, but the period and the light-curve of any one are quite constant. The light-curve of δ Cephei is given in Fig. 163 as a full line. Many stars having

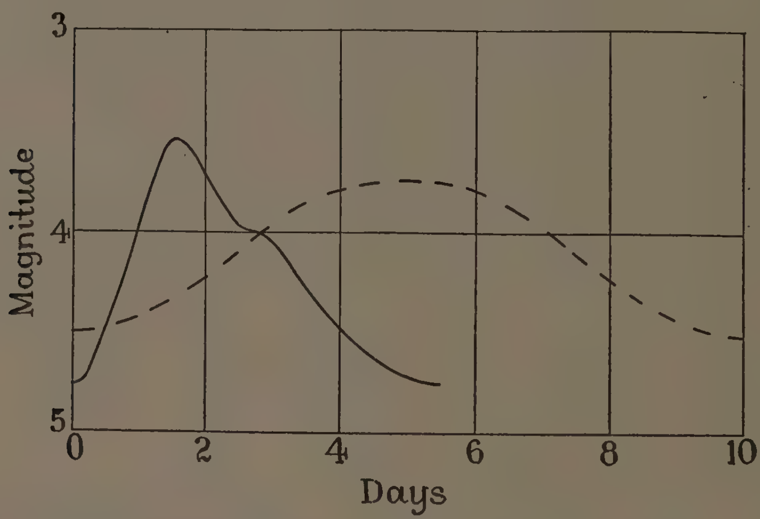


Fig. 163.—Light-curves of δ Cephei (full line) and ζ Geminorum (broken line).

short periods of less than one day are found in the globular clusters and they are often called "cluster" variables, but there seems to be no good reason for excluding them from the Cepheid group.

A star having a different light-curve is ζ Geminorum (broken line, Fig. 163). From the evidence at hand, stars of this kind form a subclass somewhat different from the ordinary Cepheids but still sufficiently like them to fall under the same general class.

The spectra of most of the stars of this group are of the F, G or K type.

For many years it was believed that the Cepheid variables were spectroscopic binary stars because the lines in their spectra showed periodic shifts in conformity with their period of light variation. One peculiarity, however, seemed to place them in a special class, for the maximum light occurred at the time of maximum velocity of approach and minimum at maximum velocity of recession. Various theories were proposed to explain this peculiarity but none appeared entirely satisfactory.

More recently a new theory known as the "pulsation" theory has been proposed. This assumes that a Cepheid variable is a giant star of low density which alternately expands and contracts and explains the shift in the spectral lines by this motion. While the theory may not at present explain all that is desired, nevertheless it seems to be the best one available.

389. The Leavitt-Shapley Period-luminosity Law.—In 1908, Miss Leavitt of the Harvard College Observatory called attention to a peculiar relationship which existed among a number of variable stars in the smaller Magellanic Cloud, a mass of stars and nebulæ in the southern heavens which looks like a detached part of the Milky Way. This relationship may be stated thus: The period of variation of these stars depends upon their brightness in such a way that the longer the period of variation the brighter the star. Since these stars undoubtedly belong to the smaller Magellanic Cloud, they are at approximately equal distances from us. The relationship could be stated more specifically as follows: The periods of this group of variables depend upon their absolute magnitudes.

The next great advance was made by Shapley, who showed, among other things, that the relationship between period of variation and absolute magnitude held for Cepheid variables wherever found. This relationship is usually called the period-luminosity law of Cepheid variation, but since it was essentially discovered by Miss Leavitt and first applied by Shapley we shall call it the Leavitt-Shapley law. The law was published by Shapley in the form of a curve which, for the purposes of this book, has been redrawn in a modified form and is given in Fig. 164.

This remarkable relationship cannot be fully explained as yet, but it seems to be an argument in favor of the "pulsation" theory of Cepheid variation. There is evidence that the Cepheids are all giant stars and it does not seem improbable that at certain periods of their development the internal forces tending to

disrupt the star are practically in balance with the gravitative force which works toward condensation. With different masses and temperatures the balance would be attained under different conditions and the pulsations therefore would have different periods.

The application of the Leavitt-Shapley law will be illustrated by an example. Let us suppose that we observe a Cepheid variable having a period of 30 days and an apparent mean magnitude[1] of +7. Using this period, the curve shows that the absolute

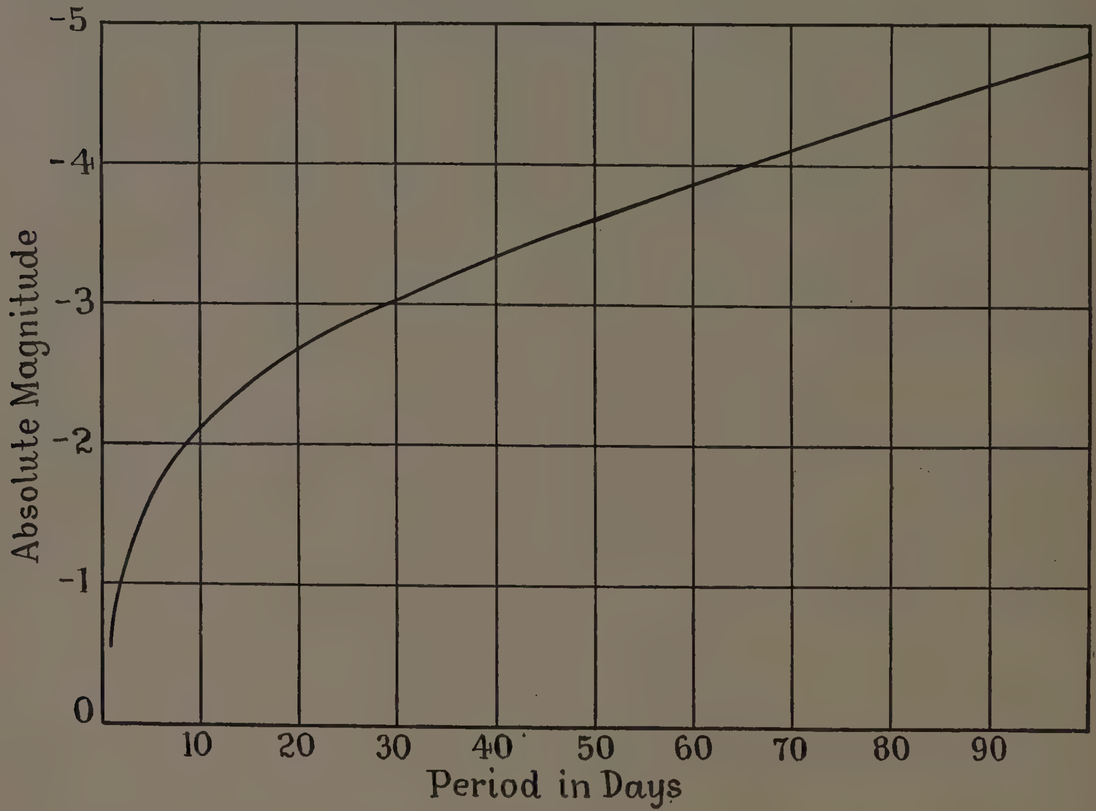


FIG. 164.—Graph of the Leavitt-Shapley law, showing the relation between the period of variation and the absolute magnitude of Cepheid variable stars.

magnitude of the star is approximately −3. The difference between apparent and absolute magnitude is 10. According to the relation between change of magnitude and distance (Sec. 355), a change of five magnitudes corresponds to a tenfold change in distance and therefore a change of 10 magnitudes corresponds to a change of 10 × 10 = 100 fold change in distance. Since, by definition, the absolute magnitude equals the apparent magnitude at a distance of 10 parsecs the star under consideration would be at a distance of 1000 parsecs.

[1] The mean magnitude used is the arithmetic mean of the magnitudes at maximum and minimum light.

Further applications of this law will be made when we study the globular star clusters.

390. Class V—Eclipsing Variables.—The classical illustration of this type is Algol (β Persei). For over 2 days this star appears to be of almost constant brightness with a magnitude of 2.3. It then begins to decrease in brightness and in about 5 hours it reaches magnitude 3.5. In another 5 hours it has recovered its former brightness and remains so for the next 2.5 days. This variation has continued with great regularity ever since its discovery by Montanari in 1667.

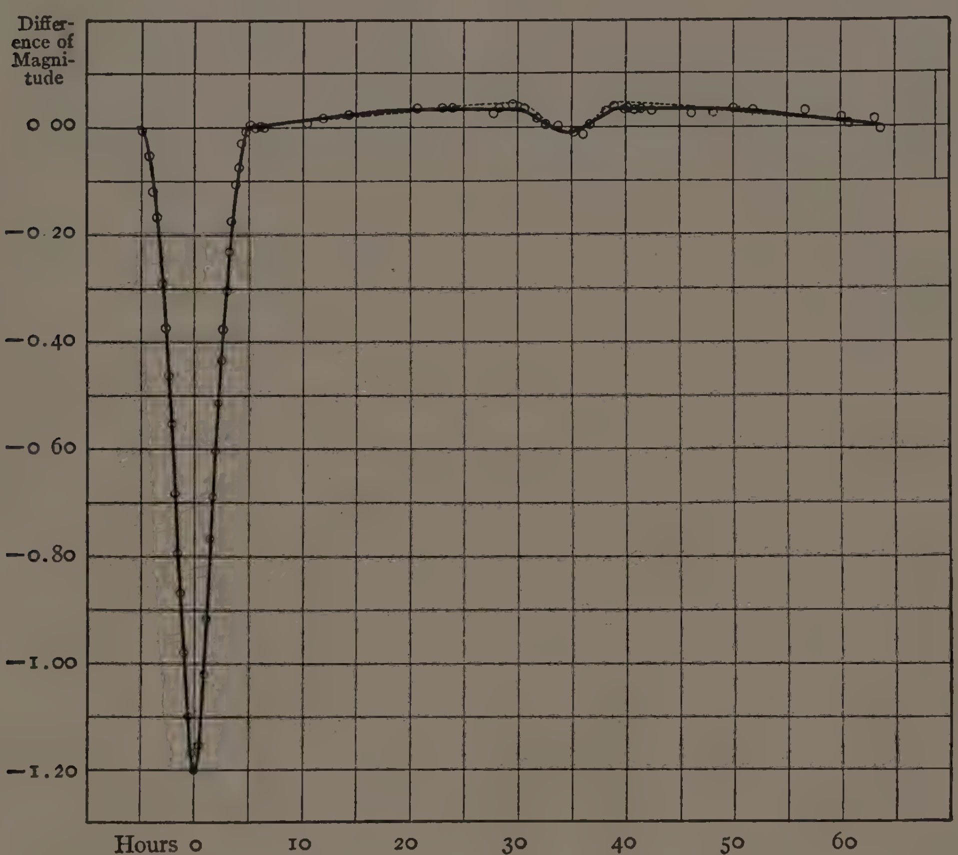


FIG. 165.—Light-curve of Algol. (*According to Stebbins.*)

The simplest explanation of the variation is that the star is not a single but a double star, one component being darker than the other, and the two moving around their common center of gravity. The plane of the orbit is turned so nearly edgewise to the line of sight that at each revolution the darker body eclipses the brighter one, cutting off most of its light.

This explanation is confirmed by spectrographic observation. Before eclipse the brighter star is found to be moving away from us, and after eclipse it is moving toward us.

The most exact study of the light variation of Algol has been made by Stebbins, now at the University of Wisconsin. His latest light-curve is given in Fig. 165. The relative orbit is shown in Fig. 166.

It will be noted that the light curve is not flat at the top. A secondary minimum occurs half way between the principal minima. This is due to the eclipse of the darker by the brighter component and shows that the darker radiates some light. The curve also slopes upward from primary to secondary minimum and downward from secondary to primary. This is an indication that the side of the darker companion which faces the

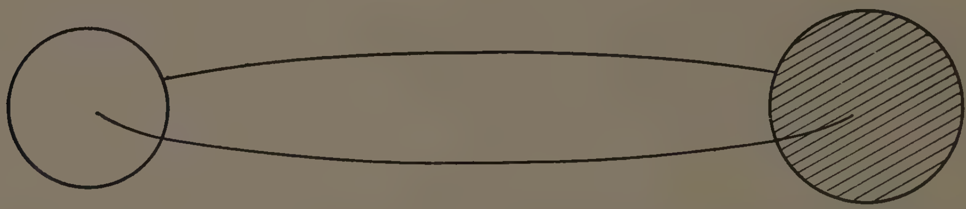


FIG. 166.—Apparent orbit and relative sizes of the components of Algol.

brighter star is somewhat brighter than the other side and after the principal eclipse we see more and more of the brighter side of the darker companion.

From the radial velocities of Algol it is possible to determine the size of its orbit, and since the light-curve gives the duration of eclipse it is clear that we have a possibility of determining the diameters of the components. Stebbins' latest results are as follows:

TABLE XIII

Ratio of radii	0.85
Area of bright body obscured at minimum	0.700
Light of bright body	0.925
Light of bright side of faint body	0.075
Light of faint side of faint body	0.045
Radius of bright body (orbit radius = 1)	0.207
Radius of faint body	0.244
Cosine of inclination	0.142
Mean density of system (sun = 1.0)	0.07
Duration of eclipse	$9^h.66$

A second example of this class of variable stars is β Lyræ. Its light-curve is given in Fig. 167. This curve is explained by

assuming two bright stars of unequal size practically in contact and alternately eclipsing one another.

There are at present about 20 stars like β Lyræ known. Their periods vary from 9^h for U Pegasi to $198^d.5$ for W Crucis.

391. With the exception of the eclipsing variables the other classes shade into each other, and it may often be a question into which group a variable star should be placed. Thus the star η Carinæ was seen by Halley in 1677 to be of the fourth magnitude. Within the next decade it became a second-magnitude star and was also of that brightness when seen by Lacaille in 1751. In 1827 it was of the first magnitude, while in December, 1837, Sir John Herschel found it to be about 0 magnitude. It soon went down to the first but in 1843 it rose to about magnitude -1. It then faded gradually to about the sixth magnitude in 1867, and is now about the eighth magnitude. The spectrum resembles that of a nova in its early stages. Such a star is not easily classfied. Another star like it is T Pyxidis, which likewise has a typical nova spectrum and has shown three maxima since 1890.

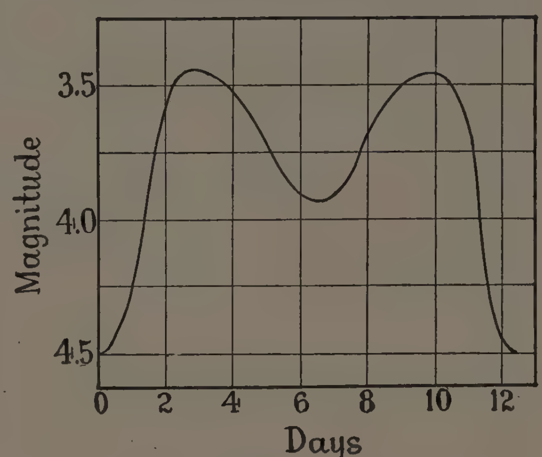


FIG. 167.—Light-curve of β Lyræ.

392. Study of Variable Stars.—The careful study of variable stars is engaging the attention of an increasing number of observers. Over 3000 variable stars are known at the present time and more are being discovered. It is likely that all stars vary in brightness to some extent and that only those whose variations are rapid, in terms of the life history of a star, can be detected by means now at our disposal.

Hagen has issued a series of charts of great value for the study of these stars. The Harvard Observatory also has issued many photographic charts for this purpose and is headquarters for the general collection of variable-star observations in this country.

The variable-star field is one in which amateur astronomers can be of great aid to the science, as the number of variables is so great that the regular observatories cannot follow them adequately. The American Association of Variable Star Observers and the

Variable Star section of the British Astronomical Association are composed largely of amateurs who are producing valuable results.

NUMBER AND ARRANGEMENT OF THE STARS

393. There is a general impression that the number of stars within reach of the naked eye is without limit, but an exact count of various regions of the sky will soon convince anyone that the actual number that can be seen at any one time is quite limited. It is doubtful if there are at any time, even with a clear sky and in the absence of the moon and of artificial illumination, as many as 2500 stars in the visible hemisphere. A telescope, however, will bring out many thousands.

It is estimated that with the 91-cm (36-inch) Lick refractor about 100,000,000 stars could be seen in the entire sky, while with the 254-cm (100-inch) reflector at Mt. Wilson over 10 times as many could be photographed.

394. The Milky Way.—One of the most conspicuous objects in the heavens on a clear summer night is the Milky Way, or galaxy. If observed carefully through the summer, fall and winter it will be seen to encircle the sky and divide it into two approximately equal parts. As soon as a telescope is used, it is found to consist of many stars, and photographs of the denser regions show literally great clouds of stars (Figs. 168 and 180).

For reasons which will soon appear it has been found convenient to take the central line of the galaxy as a fundamental circle for a system of coordinates called *galactic latitude* and *longitude.* The north pole of this circle is at R. A. $12^h\ 40^m$, Dec. $+28°$. Galactic latitude is measured north and south from the galactic circle and galactic longitude is measured eastward from the intersection of the galactic circle with the celestial equator in Aquila at R. A. $18^h\ 40^m$, Dec. $0°$.

395. The Herschel Star Gages.—The first one to investigate the Milky Way with care was Sir William Herschel. He made counts, over the northern sky, of the number of stars that could be seen in the 15′ field of view of one of his telescopes, a 45-cm (18-inch) reflector, and his son, Sir John Herschel, using the same instrument, made similar counts in the southern sky. The results of these thousands of "star gages" showed a most remarkable relation between the average number of stars seen in the field of the telescope and the location of the field with respect to the

FIG. 168.—Milky Way North of θ Ophiuchi. *(Photographed by Barnard of the Yerkes Observatory.)*

Milky Way. The following table is a brief resumé of these gages, the values being taken from Herschel's "Outlines of Astronomy."

TABLE XIV

Galactic Latitude	Average Number of Stars in Field 15′ Diameter
90°	4.2
75	4.7
60	6.5
45	10.4
30	17.7
15	30.3
0	122.0

From these figures it is evident that the Milky Way is of fundamental importance in any general consideration of the arrangement of the stars.

396. Recent Star Counts.—In 1925, Seares and van Rhijn published an extensive table, based upon star counts on plates taken at Harvard, Göttingen, Greenwich, Mt. Wilson and Oxford, which gives the average values for the number of stars per square

TABLE XV.—NUMBER OF STARS PER SQUARE DEGREE FROM THE BRIGHTEST TO MAGNITUDE m

m	Galactic latitude				
	0°	15°	30°	60°	90°
4	0.016	0.011	0.007	0.005	0.005
5	0.045	0.032	0.021	0.015	0.013
6	0.129	0.093	0.062	0.042	0.037
7	0.363	0.263	0.174	0.117	0.102
8	1.0	0.724	0.479	0.324	0.275
9	2.82	1.95	1.32	0.871	0.724
10	7.77	5.25	3.47	2.24	1.82
11	20.9	13.8	9.12	5.50	4.37
12	55.0	34.7	22.9	12.9	10.0
13	145	89.1	55.0	28.8	21.4
14	372	219	126	60.3	44.7
15	912	513	275	123	87.1
16	2,140	1,170	562	234	162
17	4,790	2,570	1,100	427	288
18	10,200	5,370	2,000	724	479
19	20,900	10,500	3,470	1,200	776
20	39,800	19,500	5,620	1,820	1,170
21	74,100	34,700	8,710	2,630	1,660

degree for 14 galactic latitudes from 0 to 90° from the brightest down to magnitude 18.5. From the regularity with which the numbers changed, they continued the table to magnitude 21. The entire table is too long to be reproduced but enough is given in Table XV to show the character of the results.

Three facts are clearly brought out by these figures.

1. Stars of all magnitudes, within the limits given, increase in number as the galactic latitude decreases.

2. This concentration is more marked for the fainter than for the brighter stars.

3. The ratio of the total number of stars down to any magnitude to the total number down to one magnitude brighter is larger in or near the Milky Way than at a distance from it.

Two terms will now be defined which we shall need in a consideration of the structure of the stellar system, namely, *star density* and *star ratio*.

397. Star Density.—This term means the number of stars in unit volume, or, to be specific, the number of stars per cubic parsec. Since the stars, on the average, are more than 1 parsec apart, there will be less than one star in each cubic parsec—in other words, the star density will be less than 1. Thus, if the star density is 0.1 in any particular region, this means that there is one star for every 10 cubic parsecs, or an average of one-tenth of a star for each cubic parsec.

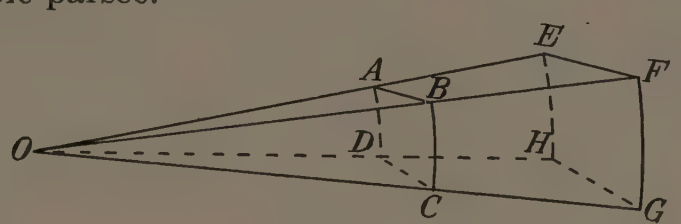


Fig. 169.

398. Star Ratio.—In Sec. 357 we noted that we can speak of the *average star*. Let us now consider a certain volume of space, *O-ABCD* (Fig. 169), the observer being at *O*. Within this volume the faintest average star will have a certain magnitude, let us assume the tenth, and be at the boundary *ABCD*. Let us then penetrate space still farther so that the volume included will be *O-EFGH*, and so that the average star in the added volume between *ABCD* and *EFGH* will be of the eleventh magnitude. If the star density is the same throughout the volume of space under consideration, then the average star of the eleventh magnitude will be 1.585 times as far away as the average star of the

tenth magnitude (Sec. 355). This means that the distance from O to the boundary $EFGH$ will be 1.585 times the distance from O to the boundary $ABCD$. From solid geometry we know that the volumes of similar solids are proportional to the cubes of homologous lines of the solids. Therefore the volume O-$EFGH$ will be to the volume O-$ABCD$, as $(1.585)^3 : 1^3$, or as 3.98:1. For convenience let us call this ratio 4:1.

By penetrating space far enough to include the average star of the eleventh magnitude we have therefore quadrupled the volume of space under consideration. If the star density is constant, we should therefore expect that the number of all the stars in the region down to the eleventh magnitude would be four times the number of stars down to the tenth magnitude. This argument holds as well for any two consecutive magnitudes. We can say therefore that, assuming uniform star density, the number of stars seen in any given area of the sky down to any magnitude m should be four times the number down to magnitude $m-1$. This ratio of 4:1 will be called the *theoretical star ratio.*

Let us now compare the results of actual star counts with the theoretical ratio, using the table of Sec. 396. Dividing each number by the one above it, we obtain the following results:

TABLE XVI.—STAR RATIOS

Magnitudes	Galactic latitude				
	0°	15°	30°	60°	90°
5: 4	2.9	2.9	2.9	2.9	2.9
6: 5	2.9	2.9	2.9	2.8	2.8
7: 6	2.8	2.8	2.8	2.8	2.8
8: 7	2.8	2.8	2.8	2.8	2.7
9: 8	2.8	2.7	2.8	2.7	2.6
10: 9	2.8	2.7	2.6	2.6	2.5
11:10	2.7	2.6	2.6	2.5	2.4
12:11	2.6	2.5	2.5	2.3	2.3
13:12	2.6	2.6	2.4	2.2	2.1
14:13	2.6	2.5	2.3	2.1	2.1
15:14	2.5	2.3	2.2	2.0	1.9
16:15	2.3	2.3	2.0	1.9	1.9
17:16	2.2	2.2	1.9	1.8	1.8
18:17	2.1	2.1	1.8	1.7	1.7
19:18	2.0	1.9	1.7	1.7	1.6
20:19	1.9	1.9	1.6	1.5	1.5
21:20	1.9	1.8	1.5	1.4	1.4

We thus see that the star ratio is nowhere equal to 4, the theoretical value; that it decreases, in general, as we include fainter and fainter stars, and that the decrease is more rapid toward the poles of the Milky Way than in its plane.

399. Results of Star Counts.—From the material of the preceding section we are led to the following interesting results: (1) The star density decreases with increasing distance from the sun.[1] (2) The decrease is more rapid in a direction at right angles to the Milky Way than in its plane. (3) Unless the star ratio increases again at some point not yet accessible to observation, we should finally reach portions of space with practically no stars in them as we went ever farther from the sun—in other words, *the stellar system is limited in extent.*

The values of the star ratio for the stars brighter than the seventh magnitude in the table are not far from the theoretical value 4, so that for the region immediately surrounding the sun the actual and theoretical values are in fair agreement. Analysis of star counts in restricted regions sometimes shows values beyond the theoretical amount, which indicates that the sun is not in the densest part of the system—in other words, it is not at the center.

400. Boundary of the Stellar System.—We shall now consider some results obtained in accordance with the "star ratio" argument. In 1922, Kapteyn published a summary of the work to which he had devoted practically his whole life. His conclusions are that, assuming the sun as a center, the stars reached by the counts are confined in a region approximately the shape of a thin watch with a thickness about one-fifth of the diameter, the greatest extension being in the plane of the Milky Way. He estimates the diameter to be about 17,000 parsecs and the thickness about 3400 parsecs if the boundary is placed at points where the star density is one-hundredth of its value in the neighborhood of the sun. The star counts of Seares and van Rhijn will lead to the same general outline but with a greater value for the diameter. Shapley's estimates will be discussed in Sec. 444.

401. The Sun's Position.—As stated in Sec. 399, there is evidence to show that the sun is not at the exact center of the stellar system, but authorities disagree as to its distance from the

[1] Either sun or earth. The relatively small distance between the two is negligible.

center. Since the Milky Way is practically a great circle in the sky, the sun must lie close to its plane. The center, as seen from the sun, would therefore be in the Milky Way, that is, in galactic latitude 0°, provided the sun is at some distance from the center. The longitude, however, is in question. Kapteyn favored the region of Cassiopeia, Shapley favors the Scorpio-Sagittarius region, while others favor the direction of Cygnus.

The distance from this center is a problem of even greater difficulty. Kapteyn has given a provisional estimate of 650 parsecs but Shapley's work shows rather conclusively that this is too small.

CHAPTER XVII

THE GLOBULAR STAR CLUSTERS AND THE NEBULÆ

THE GLOBULAR CLUSTERS

402. The Hercules Cluster.—In the summer and fall the constellation Hercules is above the horizon in the early hours of the night. Between the stars η and ζ Herculis and about one-third of the way from the former to the latter a moderately good

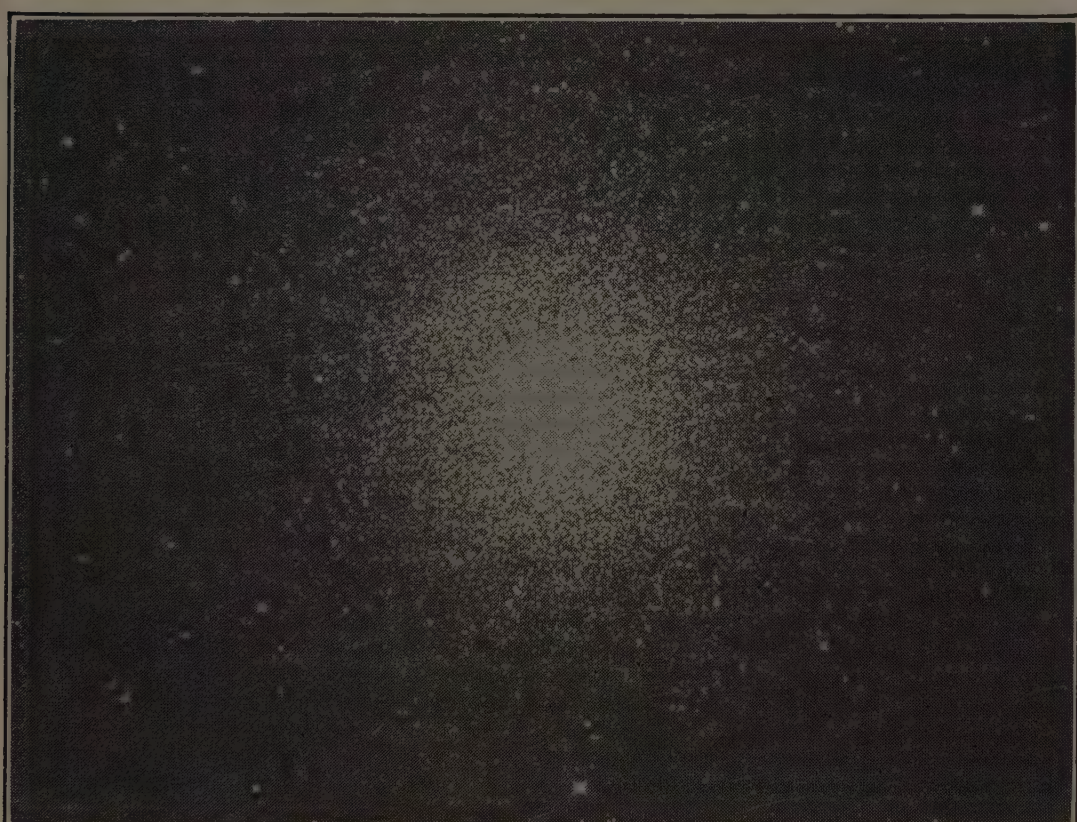


FIG. 170.—The great globular star cluster in Hercules (N. G. C. 6205). (*Photographed by Ritchey at the Mt. Wilson Observatory.*)

eye will detect an object looking like a faint hazy star. Examination with a small telescope of about 3-inch aperture and with moderate magnification will show a bright disc with hazy edges. A 5-inch telescope will begin to resolve this into a mass of stars, and telescopes of larger aperture will show correspondingly more

and fainter stars. In order to appreciate the wonderful beauty of this object, however, we must resort to photographic telescopes of the largest size. These reveal to us the object shown in Fig. 170. Counts of the stars made at the Mt. Wilson Observatory show that there are at least 50,000 stars in this one cluster and it is believed that very long exposures would reveal at least 100,000.

403. Number and Shape of Globular Clusters.—There are now about 90 objects of this character known to astronomers. They are called *globular clusters* because there is evidence which shows that they are all approximately spherical in shape. In some cases Shapley has shown that the outline is slightly elliptical instead of circular. The Hercules cluster is the finest of its class in the northern sky; in the southern heavens the ω Centauri cluster alone exceeds it in apparent size.

404. Distance and Dimensions of Globular Clusters.—The distance and dimensions of the globular clusters are questions which were often discussed from the time of their discovery up to the present time. One question in particular was considered most frequently: Are these clusters within the limits of our own system of stars or are they beyond it? No particularly good arguments could be advanced for either side until Shapley published his remarkable series of papers on the globular clusters in 1914 to 1918. He found three methods of determining their distances.

405. First Method.—Bailey of the Harvard Observatory had discovered some years ago that in certain globular clusters there were many variable stars; thus in N. G. C. 5272[1] there were 132 and in N. G. C. 7078 there were 51 variables. Other clusters had fewer variables and in some clusters none were found. Some of these variables were of the ordinary δ Cephei type and others of the so-called "cluster" type, but, as stated in Sec. 388, there seems to be no valid reason for differentiating between the δ Cephei variables having periods longer than one day and the cluster type variables having periods of about half a day. Shapley therefore assumed that they were essentially alike and used these as well as 11 Cepheids not in the clusters, and the variables of this type found by Miss Leavitt in the smaller Magellanic Cloud, in deriving the period-luminosity curve (the Leavitt-Shapley law, Fig. 164). By means of this curve he was able to

[1] N. G. C. refers to Dreyer's New General Catalog of Nebulæ and Clusters.

determine the distances of those clusters having Cepheid variables by the principle discussed in Sec. 389.

406. Second Method.—Shapley next showed that there is a practically constant difference of magnitude between the 25 brightest stars in each cluster and the mean magnitude of the short-period variable stars. This difference in magnitude amounts to 1.28. Since the evidence indicates that the short-period variables have very nearly the same absolute magnitude, it follows that the brightest stars in these clusters are also very nearly of the same absolute magnitude, -1.5. Accordingly, we see that, by determining the apparent magnitude of the brightest stars in each cluster, the difference between this value and -1.5 enables us to determine the distance of the cluster by the method of Sec. 355.

407. Third Method.—As a final step Shapley examined the distances of the clusters obtained by the two methods described above and the apparent diameters of the clusters, and brought out the significant fact that all globular clusters investigated seemed to have about the same actual dimensions. This means that if we photograph two clusters and the diameter of one is double that of the other, then the second is twice as far away as the first.

Table XVII shows the distances in parsecs of a few clusters obtained by Shapley by the three methods described above.

Table XVII.—Distances of Globular Star Clusters in Parsecs

N. G. C.	Method			Weighted mean
	Variable stars	Brightest stars	Diameter	
6205	......	11,200	11,000	11,100
7006	......	......	66,700	66,700
7078	14,900	14,500	16,900	14,700
7089	15,400	16,700	13,900	15,600

By the use of these methods Shapley published a list of 69 clusters for which he had been able to determine parallaxes. Their distances range from less than 7000 to 67,000 parsecs, or from 23,000 to 220,000 light-years. One-fourth of all the globular clusters appear to be more than 30,000 parsecs (100,000 light-years) distant.

408. The Distribution of the Globular Clusters in Space.—We shall next give two diagrams published by Shapley which show the distribution of these clusters in space. In Fig. 171 the sun is assumed at the center of the figure and the plane of the figure is the plane of the Milky Way. The scale of distances is shown by the concentric circles, and galactic longitudes are marked on the outermost circle. The arrows give the distances to scale from the plane of the Milky Way, the full-line arrows belonging to clusters north of this plane and the broken-line arrows to clusters south of

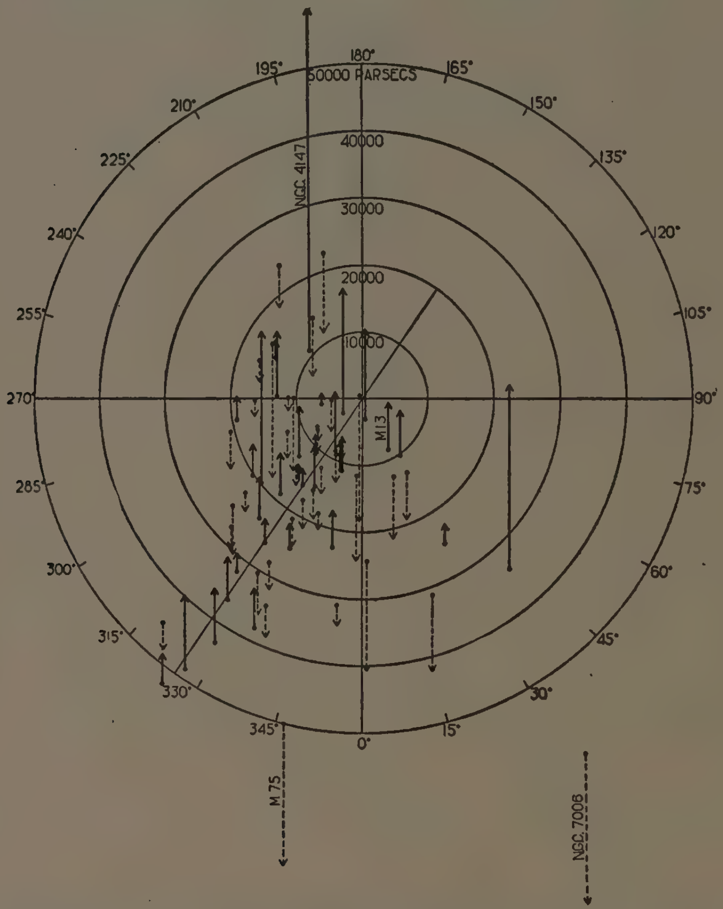


FIG. 171.—Distribution of the globular star clusters in galactic longitude. (*According to Shapley.*)

it. We must imagine each arrow turned vertically to the plane of the paper around the dot at one end. The position of the cluster is then given by the point of the arrow. A remarkable distribution is shown by the figure. There are few short arrows. This means that most clusters are at some distance from the plane of the Milky Way. Most of the clusters are found within one quadrant from galactic longitude 270° to 0° and none at all in the opposite quadrant.

The arrangement with respect to the plane of the Milky Way is shown more clearly by Fig. 172. This represents a section

through the preceding figure along the line through the center to longitude 325° and the clusters then projected on the plane of the section. The position of the sun is indicated by the small cross. The unit of distance is 100 parsecs, so that the side of each square represents a distance of 10,000 parsecs, or 33,000 light-years. On the scale of the figure the actual diameters of the clusters are about one-fifth of the diameter of the circles and dots.

409. Size and Star Density.—Having now obtained a knowledge of the distances of the globular clusters, we may next consider the question of their actual size and star density. From the relation between apparent diameter and distance we find that the diameter of such a cluster is approximately 500 light-years,

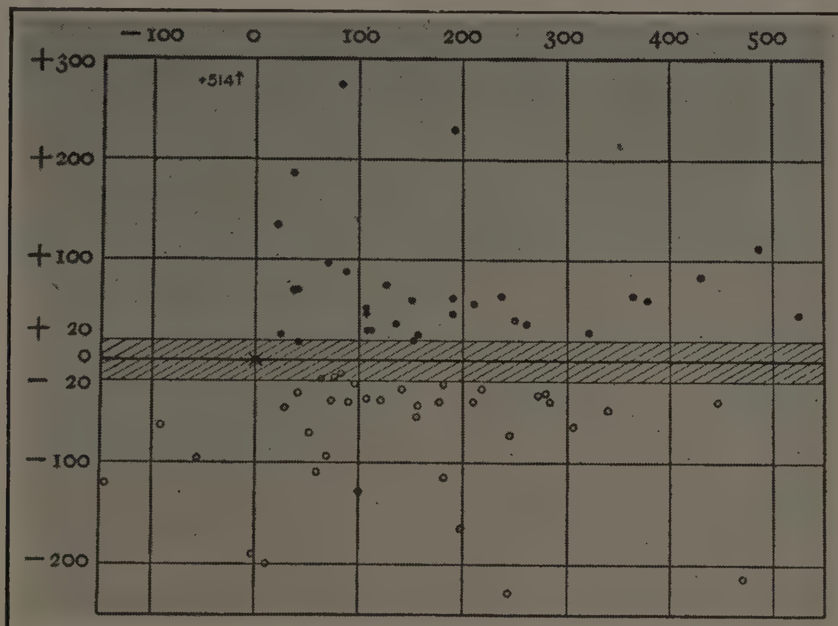


FIG. 172.—Distribution of globular clusters in galactic latitude. (*According to Shapley.*)

or 150 parsecs. The volume of such a sphere will be approximately 1,770,000 cubic parsecs. On the assumption of 100,000 stars in a cluster, the mean star density becomes about 0.06, a value not very different from 0.045, the star density in the neighborhood of the sun as given by Kapteyn. The actual density in a cluster varies, however, being much above the mean at the center and much below near the outer boundary.

The results of Shapley's work as given above have been the cause of a great deal of discussion in astronomical circles and some good authorities have expressed doubt as to their accuracy and maintained that the distances are altogether too large. It cannot be denied that at the present time we cannot insist on their absolute accuracy because of certain assumptions involved in

the problem, yet no one has succeeded in actually disproving these assumptions and additional evidence is coming in from other sources which confirms these results to a greater or less degree. Later work may make it necessary to change the values to some extent but thus far they seem to be of the right order.

410. Spectra and Radial Velocity of the Globular Clusters.—In 1909, Fath investigated the spectra of the brighter stars of several clusters and in three following years added some others. The observations showed that in some clusters the mean spectrum of the brighter stars is of approximately F type, while in others there was evidence of both F and G types. These results were confirmed and much additional work accomplished by V. M. Slipher. No way has yet been found to determine, with any degree of accuracy, the individual spectral types of the stars in clusters, although such information would be of the greatest value in studying the development of these great aggregations of stars.

More recently V. M. Slipher of the Lowell Observatory and others have succeeded in determining the radial velocity of 18 of the clusters. The velocities with respect to the sun range from −350 km per second for N. G. C. 6934 to +225 km per second for N. G. C. 6333. One-half of the 18 are approaching the sun, eight are receding and one appears stationary. It may be a significant fact that so many of these clusters are approaching the sun, for this means, in turn, that they are approaching the plane of the Milky Way. Can it be that the great mass of stars composing our stellar system is attracting these clusters to such an extent that they are being drawn in? The question is of the greatest interest, but care must be taken not to generalize too much on such a limited amount of material.

THE NEBULÆ

411. There are scattered about in the sky many objects which appear more or less diffuse in character when looked at through the telescope and they were called *nebulæ* by the early observers because of their nebulous appearance. Later, better telescopes showed that some of these objects were really star clusters, but others resisted every ordinary effort at resolution into stars. The latter are still termed nebulæ although one large subdivision may have to be renamed as we shall see later.

412. Classification.—According to their form, nebulæ were classified as follows: diffuse or irregular, ring, planetary and spiral. More recently another class, the "dark" nebulæ, has been added.

A better classification, however, would be one depending on the physical characteristics as shown by the spectra of the nebulæ. Such a one would be as follows: (1) nebulæ having bright-line spectra; (2) dark nebulæ, or those shining by reflected light; (3) nebulæ having absorption spectra. Such a classification is more nearly in accord with differences in physical conditions.

Nebulæ Having Bright-line Spectra

413. Forms.—To this group belong objects of a great variety of forms. Some, like the Great Nebula in Orion (Fig. 173) and

Fig. 173.—Great nebula in Orion. (*Photographed by Wilson at the Goodsell Observatory.*)

the Trifid Nebula in Sagittarius (Fig. 174), are great masses of luminous gases of enormous extent. Their dimensions must be measured in light-years.[1] Campbell and Moore obtained radial

[1] Adopting a distance of 200 parsecs for the Orion nebula, the diameter as shown in the photograph is about 2 parsecs, or 6.5 light-years.

velocities ranging from 10 to 23 km per second (6 to 14 miles) for the central parts of the Orion nebula. These results show that tremendous streams of nebulous matter are being intermingled in chaotic fashion, as no regularity of motion was apparent.

Another form is illustrated by the Ring Nebula in Lyra (Fig. 175). Visually, this nebulous mass appears like a small, comparatively smooth oval, but photography has shown it to be of a far more complex structure, as is evident in the figure.

FIG. 174.—Trifid nebula in Sagittarius. (*Photographed at the Mt. Wilson Observatory.*)

A third form is that of the planetary nebulæ. These objects were given this name in the early days, because about the only thing that could be noted visually was a small disc with diffuse edge. In some a faint stellar nucleus could be seen. It was not until astronomical photography had reached the high development of recent years that the true forms of these small objects became known. Figure 176 shows an interesting example of the planetary type.

A fourth form is that of the "network" nebulæ in Cygnus. The exquisite beauty of these is shown by an example in Fig. 177.

414. Spectra.—The spectra of all these various forms consist almost exclusively of bright lines except that the nuclei of the planetary nebulæ appear to be O-type stars. Two known gases, hydrogen and helium, are certainly present in all of them. Wright of the Lick Observatory has shown the probability of some of the other lines being ascribed to carbon and nitrogen; other lines, always present and among the most prominent in the nebular spectrum, cannot be ascribed to any known element. These

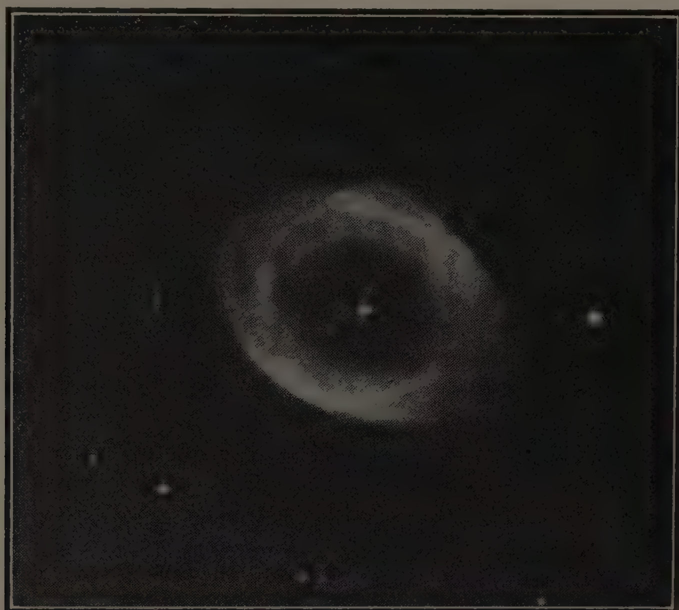


FIG. 175.—Ring nebula in Lyra. (*Photographed at the Mt. Wilson Observatory.*)

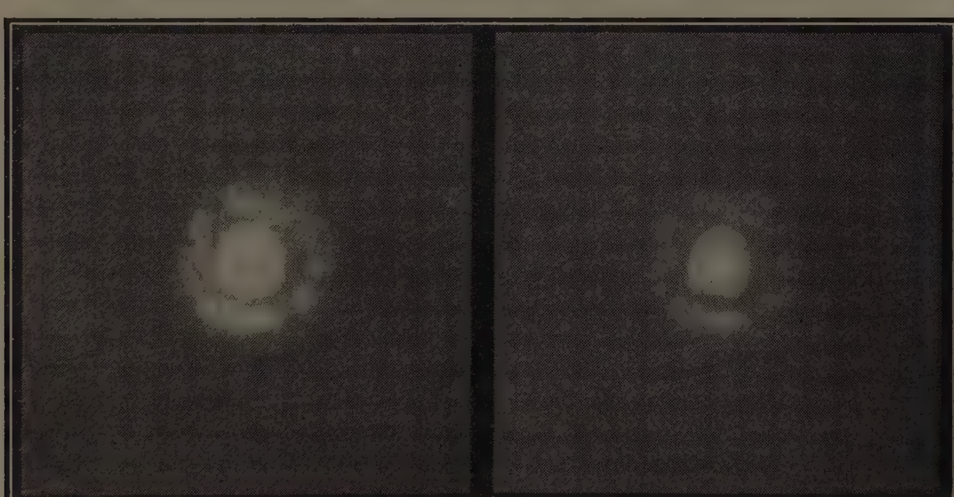


FIG. 176.—Planetary nebula N. G. C. 2392 in Gemini. The two exposures show details in outer portions and near nucleus respectively. (*Photographed at the Mt. Wilson Observatory.*)

unidentified lines are ascribed provisionally to a hypothetical element "nebulium" because of their appearance in the nebulæ.

Small objects like the ring and planetary nebulæ lend themselves readily to examination by the slitless spectrograph. Accordingly, instead of having merely bright lines (the images of the slit), the spectrum will consist of a series of images of the

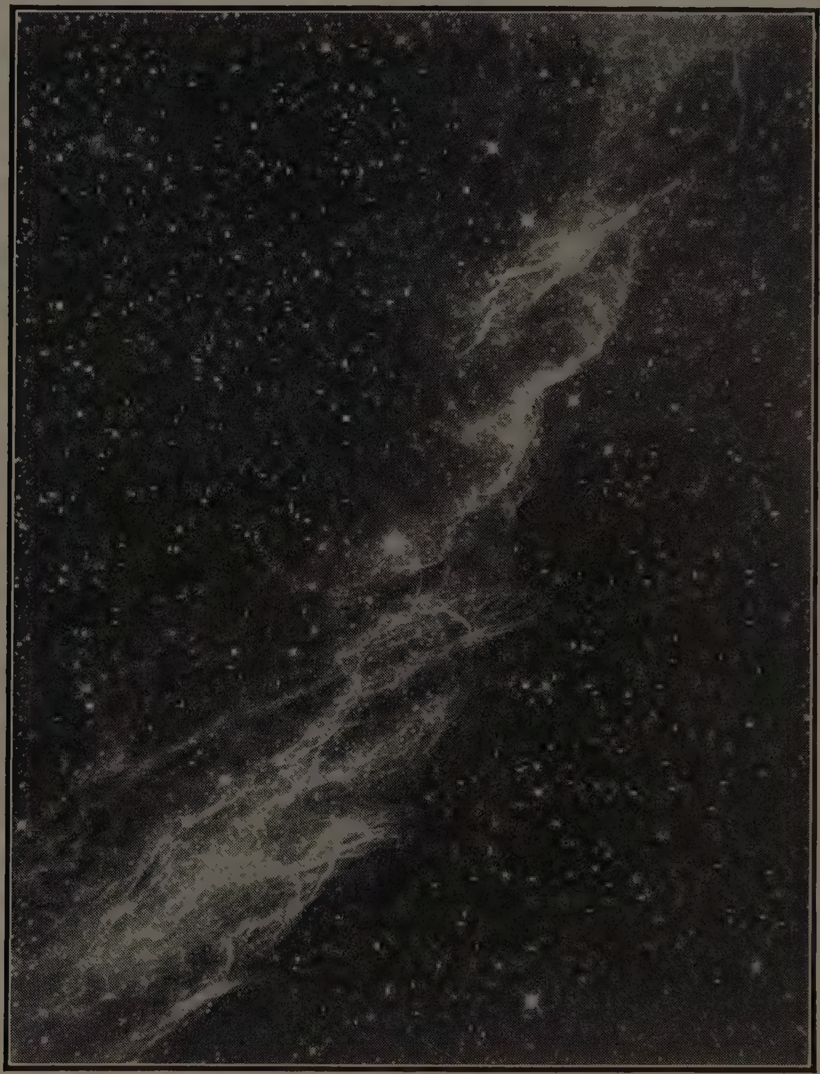


Fig. 177.—Network nebula in Cygnus. (*Photographed at the Mt. Wilson Observatory.*)

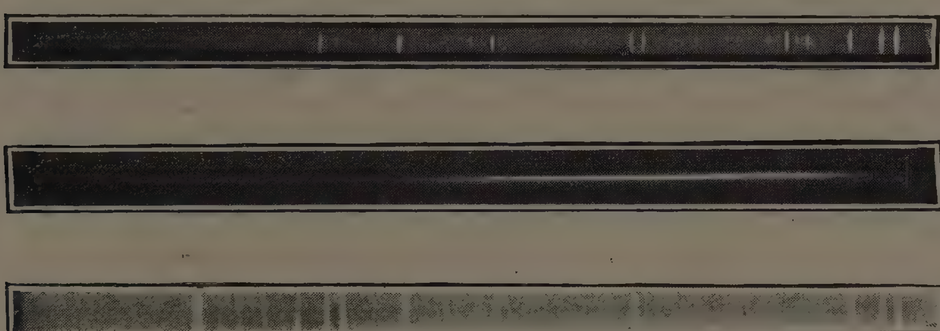
nebula itself, each image formed by the light of a single wave-length, and, if a reasonable dispersion is used, these images will be separated on the photographic plate.

The results of the use of the slitless spectrograph on these small objects present many points of interest. For example, it is found that the images will be neither of the same size nor of precisely the same shape. This indicates either a lack of uniformity

in the composition of the nebula or, possibly, a variation in the cause of the luminosity. Which of the two is the correct interpretation, or whether both are operative, cannot be decided at the present time.

Another interesting fact concerning the spectra of the bright-line nebulæ is that the relative intensities of the lines vary not only from nebula to nebula, but also in some cases in different parts of the same nebula.

Wright has published a list of 70 bright lines found in the spectra of nebulæ, but in not a single instance were all these lines present in any one nebula. Some might have been added by increased exposures, but it seems more probable that there is not only an actual difference in relative intensities of the lines but also that there is a real difference existing in the nebulæ, either in their composition or in causes producing their luminosity.



A

B

C

FIG. 178.—Spectra of gaseous nebulæ: *A*. Planetary nebula N. G. C. 7027; *B*. Planetary nebula N. G. C. 2392, spectrum of nucleus predominant; *C*. Orion nebula. (*Photographed by Wright at the Lick Observatory.*)

415. Rotation, Etc.—Campbell and Moore in 1918 published a very complete spectrographic investigation of 125 bright-line nebulæ which were bright enough to yield results with exposures of 33 hours or less. One of the results of this investigation was to show that most of the planetary nebulæ having an elliptical outline are in rotation about the shorter axis. The rotational velocity near the center is greater than at the edge of the disc. The rotation periods obtained were 12,460, 132,900 and 967 years in three cases. Using the rotational velocities observed and making certain reasonable assumptions as to the position of the axis of rotation, etc., they computed the masses of these nebulæ. The results gave values of 162, 14 and 19 times the mass of the sun, respectively. The second value in each case refers to the ring nebula in Lyra.

Another of their results was the determination of the radial velocities of the bright-line nebulæ. Velocities with respect to the sun range from +309 to −145 km per second.

416. Distance.—The distances of most of the bright-line nebulæ are unknown, but their relation to the stars is such that it seems reasonable to suppose they belong to our stellar system. The parallaxes thus far obtained are as follows:

TABLE XVIII

N. G. C.	Parallax	Observer
40	0″.002	van Maanen
2022	0.010	van Maanen
6720	0.004	van Maanen
6720	0.015	Newkirk
6804	0.020	van Maanen
6905	0.013	van Maanen
7008	0.014	van Maanen
7293	0.039	van Maanen
7662	0.023	van Maanen

The object N. G. C. 6720 is the ring nebula in Lyra. Newkirk used plates taken at the Lick Observatory and van Maanen plates taken at the Mt. Wilson Observatory. The difference in

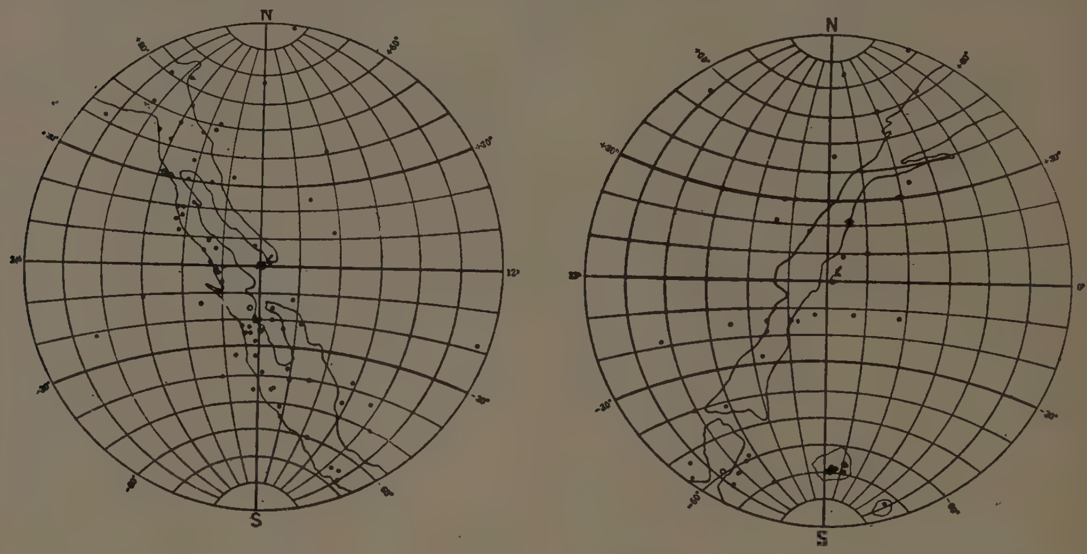


FIG. 179.—Distribution of bright-line nebulæ. (*According to Campbell and Moore.*)

the results is a good indication of the difficulty of the problem. In 1922, Gingrich determined a parallax of +0″.0095 for five stars which appeared to be involved in a small diffuse nebula

in the region of B. D. +31°643 in Perseus. This value for the parallax of the stars may be taken as the value for the nebula surrounding these stars.

417. Relation to the Milky Way.—The bright-line nebulæ, for the most part, lie in or near the plane of the Milky Way or in the Magellanic Clouds. Figure 179, taken from Campbell and Moore's monograph, shows their distribution.

418. Cause of Luminosity.—The cause of the luminosity of the bright-line nebulæ is not clear, but a paper published in 1922 by Hubble of the Mt. Wilson Observatory affords a clue. He finds that when the spectrum of a star involved in the nebulosity is of type O the nebula gives a bright-line spectrum; furthermore, that the brightness of the nebulosity in the diffuse nebulæ diminishes inversely as the square of the distance from the involved star. This clearly seems to point to the star as the source of the luminosity. The mechanism is not clear, but it may be analogous to that which causes the aurora (Sec. 163). Should this prove to be the case, then we can say at least that the luminosity of the nebulæ is produced by electrified particles shot out by the stars within the nebulosity.

The Dark Nebulæ, Etc.

419. In Fig. 180, which shows a portion of the Milky Way, there is a region almost devoid of stars. A natural explanation for such a dark region is that there are no stars there and that we are simply looking out into the depths of space beyond. Such an explanation might appear reasonable if there were only a single example, but there are many such.

Figure 181 shows a nebulous region near ζ Orionis. The illustration tells its own story. It hardly seems possible to look at it and still doubt the existence of a cloud of dark matter lying in front of the bright nebulous masses.

But there is still further evidence of matter in space, aside from the planets, which is not self-luminous. Figure 182 is a reproduction of a photograph of the Pleiades. Around many of the stars great masses of nebulosity are seen. These nebulæ look very much like some of the diffuse, bright-line nebulæ. In 1912, V. M. Slipher investigated the spectra of the nebulæ in the Pleiades and found not a single bright line. By making exposures totaling 21 hours on a single plate he found that these

nebulæ showed an absorption spectrum which matched, line for line, the spectra of the stars within their boundaries. The only reasonable explanation of these spectra is that they are produced by starlight reflected from the particles composing the nebulæ. We therefore seem justified in holding that if the stars were extinguished, these nebulæ would be dark nebulæ like the others considered above. Several other objects which show properties similar to the Pleiades nebulæ have been found since Slipher's original discovery.

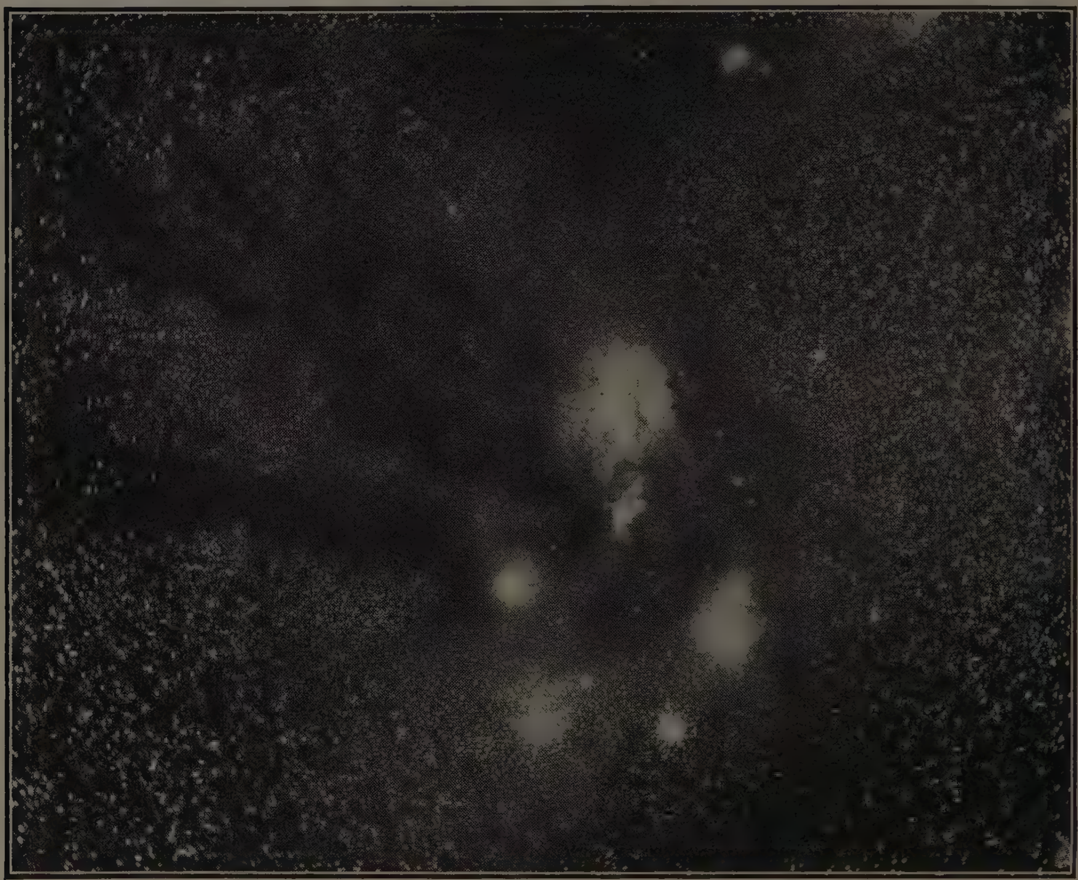


Fig. 180.—Milky Way near ρ Ophiuchi. (*Photographed by Barnard at the Yerkes Observatory.*)

For some years it has been known that certain stars with a variable radial velocity show absorption lines of calcium which indicate either no variation in velocity or a very much smaller variation than the other lines in their spectra. The best explanation at the present time is that these calcium absorption lines are caused by clouds of calcium in the vicinity of the stars, but that these clouds do not belong to the stellar atmospheres. In 1925, Struve of the Yerkes Observatory showed that in various regions in or near the Milky Way this calcium absorption phenomenon is

FIG. 181.—Region near ζ Orionis. (*Photographed by Duncan at the Mt. Wilson Observatory.*)

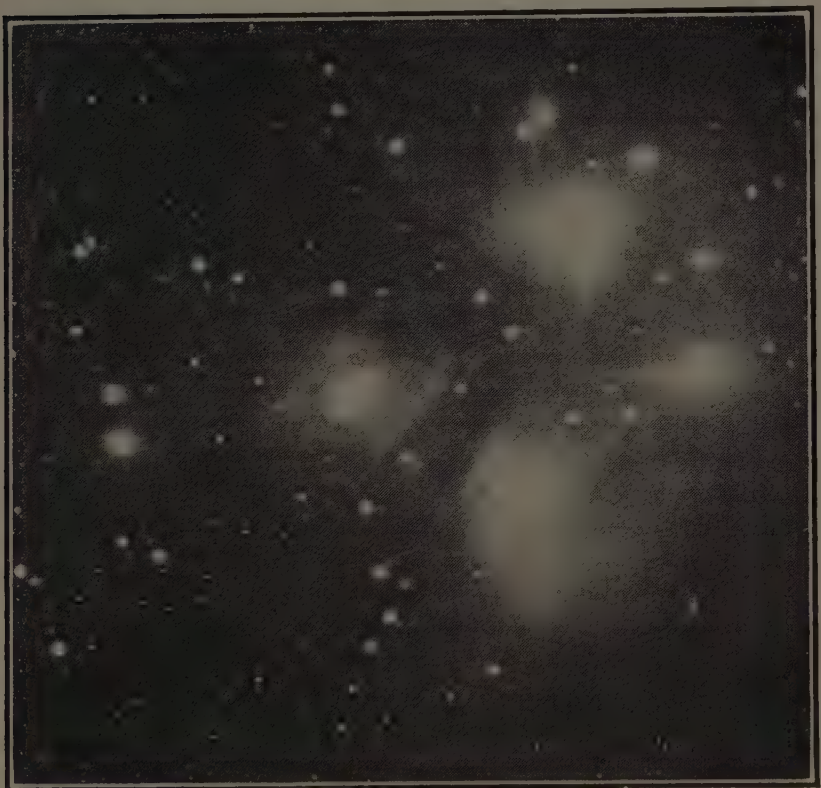


FIG. 182.—The Pleiades nebulosity. (*Photographed by Wilson at Observatory.*)

to be found over extended areas. We thus have additional evidence of non-luminous matter in space.

Hagen, the director of the Vatican Observatory, as the result of visual observations, reports a large amount of dark matter over most of the sky. Other observers have not as yet corroborated these observations. As it is a matter of great importance, it is hoped that before long the problem will be attacked by other competent observers.

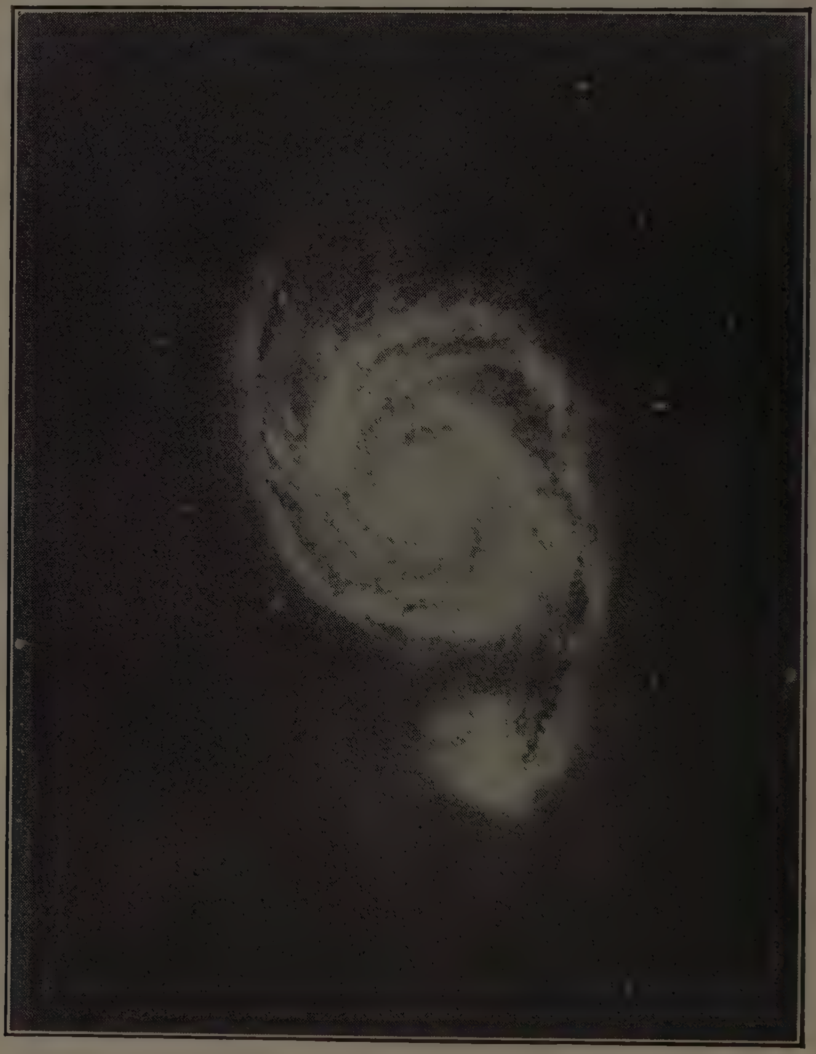


Fig. 183.—The "whirlpool" nebula, N. G. C. 5194–5195, in Canes Venatici. (*Photographed at the Mt. Wilson Observatory.*)

Nebulæ Having Absorption Spectra

420. Form.—The nebulæ belonging to this group are nearly all of spiral form. Figures 183 and 184 show two examples. The first of these is the famous "whirlpool" nebula in Canes

Venatici, the first spiral ever discovered. The second is the equally well-known Andromeda nebula, which is the largest of its kind and which is faintly visible to the naked eye.

The "whirlpool" nebula exhibits the typical form except for the large mass at the end of one of the spiral arms. The center of the nebula, usually called the nucleus, is the brightest part of the

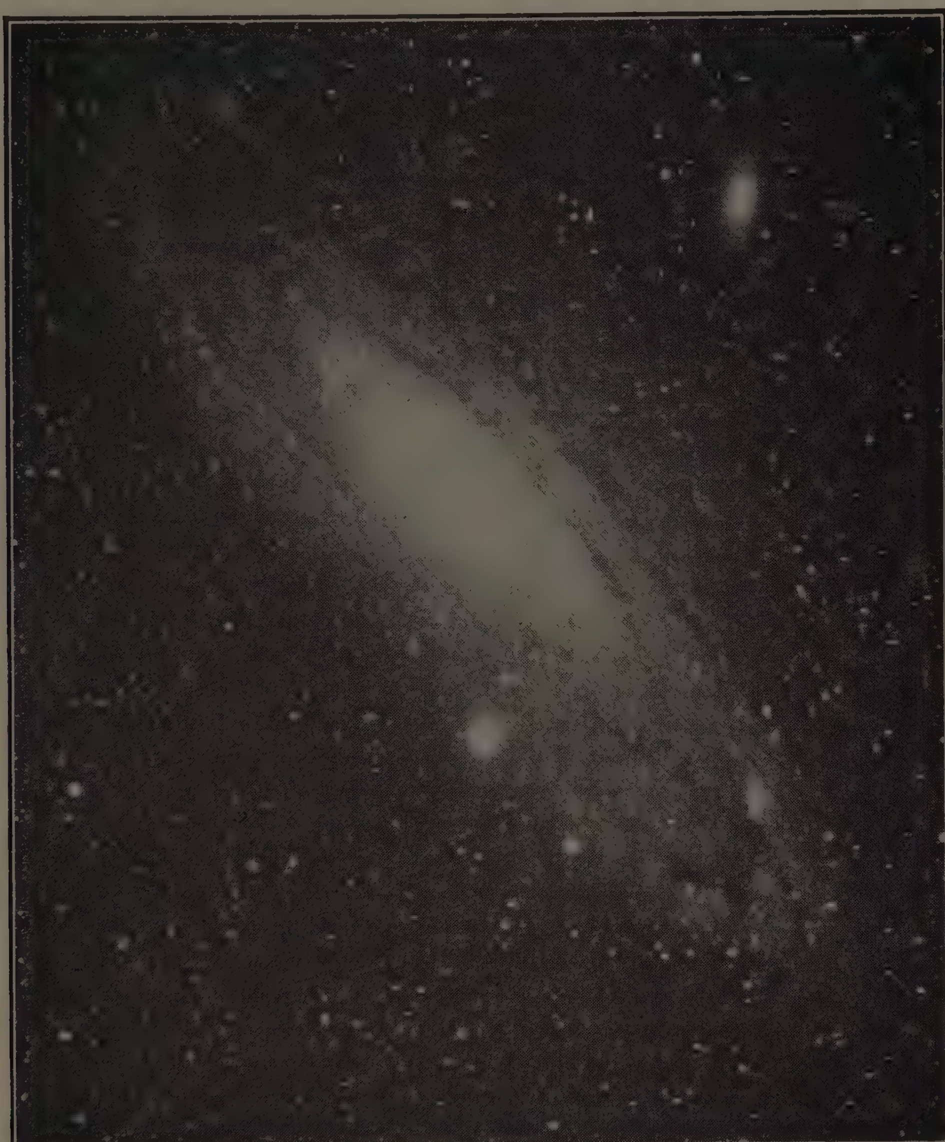


FIG. 184.—The great nebula in Andromeda. (*Photographed by Wilson at the Goodsell Observatory.*)

object. From opposite sides two spiral arms leave the nucleus and encircle it. Sometimes these spiral arms are broad, as in this case, while in others they are comparatively thin. Usually the arms are more or less irregular in structure, having many knots or condensations. Some of these condensations are hazy in appearance and irregular in outline, while others are small and round

like stars. In some cases most of the matter seems to be in the arms, while in others the central mass predominates. The arms of the spiral lie approximately in a plane. When this plane is not at right angles to the line of sight the general outline of the nebula is elliptical; while, when it is approximately in the line of sight, the nebula looks like the one in Fig. 185.

This figure also illustrates another feature which is frequently found in the spirals seen more or less edgewise, namely, the dark rift across the nucleus. Such evidence as we have favors the view that these rifts are not due to absence of nebular material but to

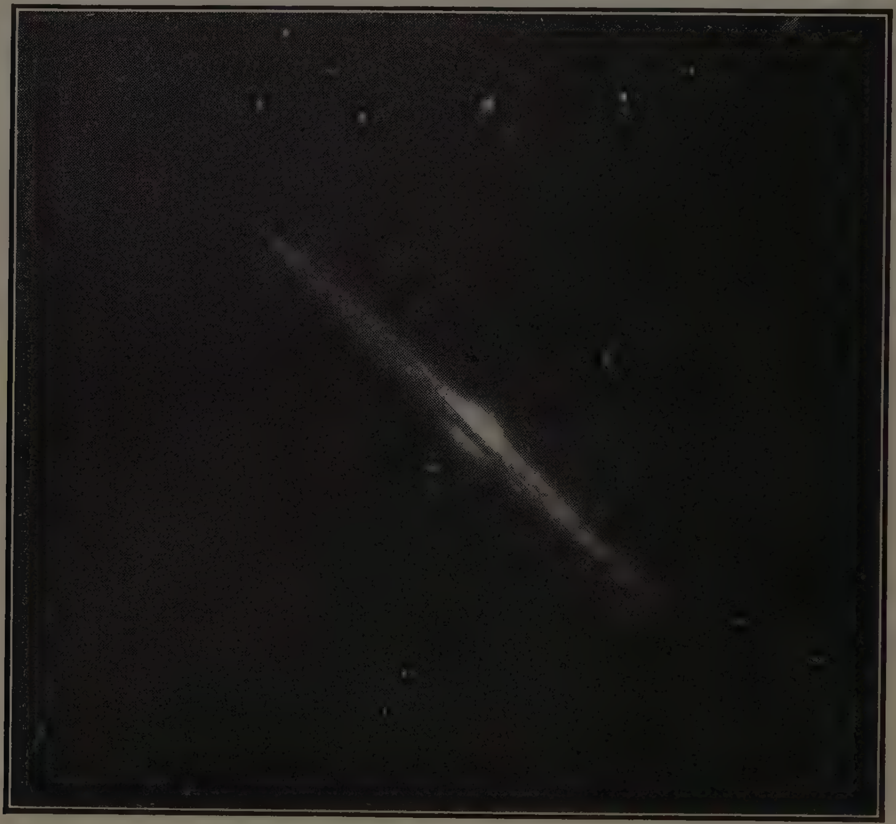


Fig. 185.—Spiral nebula seen edge-on. N. G. C. 4565. (*Photographed at the Mt. Wilson Observatory.*)

occulting matter about the nebula. H. D. Curtis has published photographs of 78 nebulæ, mostly spirals, taken with the Crossley reflector of the Lick Observatory, which show such absorption or occulting effects.

The theory is that one of the arms of the spiral is seen projected against the brighter nucleus and that the material of the arm cuts off a considerable portion of the nuclear light. We thus have further evidence of the presence of non-luminous matter in space.

421. Proper Motions.—Very little is known about the proper motions of the spiral nebulæ. Curtis obtained an average annual proper motion of $0''.033$ for 66 spirals from plates taken at the Lick Observatory between 1898 and 1915 but says the measures are not especially satisfactory. The most that it seems safe to affirm at the present time is that the proper motions are very small.

422. The Spectra of Spiral Nebulæ.—From 1908 to 1912 Fath succeeded in photographing the spectra of 10 of the brighter spirals. Nine of them showed spectra of G or K type. The tenth, N. G. C. 1068, gave a spectrum of bright lines or bands and a few absorption lines. Later, V. M. Slipher of the Lowell Observatory and Wolf at Heidelberg took up the problem. Their results confirmed the first work, and one spiral was found giving an F-type spectrum.

Slipher, moreover, succeeded in making a great advance by determining the radial velocities of 39 of these objects. The velocities obtained were extraordinary and range from -300 to $+2000$ (N. G. C. 584) km per second. Of these 39 nebulæ only five have negative velocities, *i.e.*, they are approaching us. The remaining 34 are all receding. The average velocity is about $+600$ km. Wright, Pease and Wolf have also investigated the velocities of some of the spirals and confirm the high values first obtained by Slipher.

423. Rotation.—Slipher also succeeded in showing that the lines in the spectra of some of the spirals were inclined, which implies that they are in rotation. Thus, in the case of N. G. C. 1068, a point $1'$ of arc from the nucleus on one side was moving toward us at a velocity of 300 km per second as compared with the velocity of the nucleus, and a point on the opposite side was moving away at the same rate. In some instances the spectral lines are curved in such a way that they indicate greater angular velocities at points near the nucleus than at points farther away. Such nebulæ therefore do not rotate as a unit.

Van Maanen attacked the rotation problem in a different manner. By comparing photographs taken at the Lick and Mt. Wilson observatories from 10 to 17 years apart he found evidence of rotation by measuring the positions of small condensations in the nebulæ with respect to stars in the vicinity. Thus far he has published results on seven spirals. His measures show minute displacements of such a character that they imply movement of

matter away from the nucleus along the arms of the spirals and a rotation of the arms about the nucleus. This rotation in each instance was in the direction "concave side forward"—in other words, the arms are winding about the nucleus. For the rotation periods of the spirals N. G. C. 598 (Fig. 186), 3031, 5194–5195 and 5457 he has obtained values of 160,000, 58,000, 45,000 and 85,000 years respectively. The results for 5194–5195 have been confirmed by Lampland and Kostinsky, but Schouten obtained results pointing to a considerably larger rotation period for the same nebula. Lundmark measured the same plates as van Maanen with the same instruments for N. G. C. 598 but obtained a rotational period over 10 times as large.

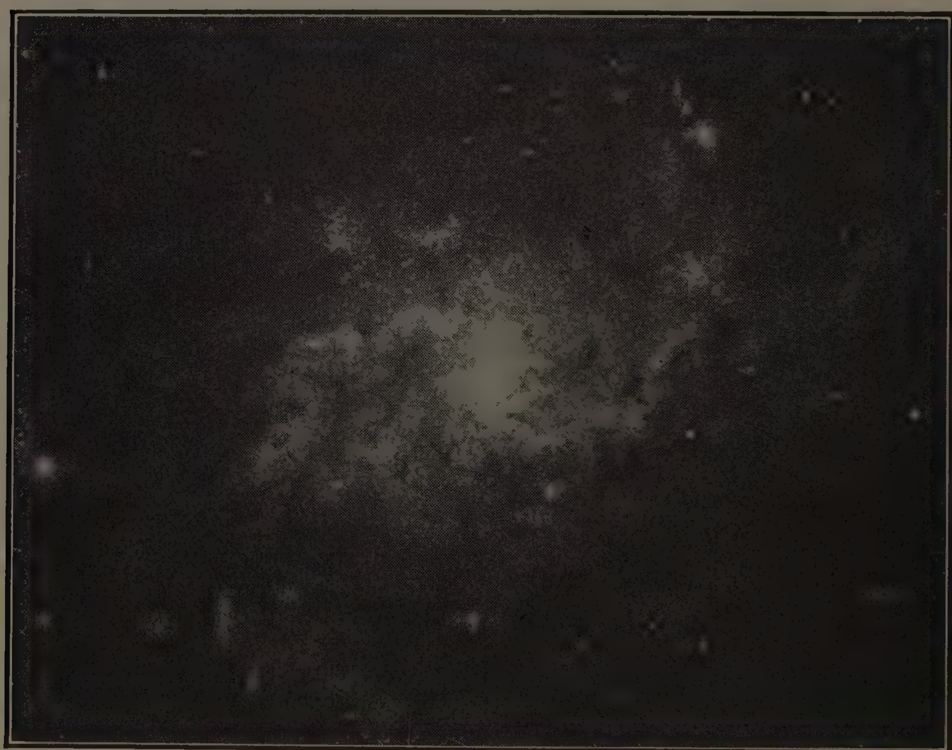


Fig. 186.—Spiral nebula, N. G. C. 598. *(Photographed at the Mt. Wilson Observatory.)*

The spectrographic method of detecting rotation by means of the inclination of the spectral lines has been used by Slipher, Pease, Wolf and Wright. Their results confirm those of van Maanen to the extent that they show material to be moving away from the nucleus. Unfortunately, the nebulæ best suited for the spectrographic method, namely, those whose planes are inclined at a small angle to the line of sight, are the ones least suited to detect displacements by direct measurements of the photographs,

since those whose planes are most nearly at right angles to the line of sight are best adapted to the second method.

424. The Distribution of Spiral Nebulæ.—There are perhaps 500 objects of this class which have been proved to be spirals. They range in size from the Great Andromeda nebula, which is about 2° in length, to small ones which show definite spiral structure only upon careful examination. By far the larger number of nebulæ found on the photographic plates are too small to show much structure; they appear for the most part merely as elliptical nebulous masses even on large-scale photographs. There does not seem to be any valid reason, however, for believing all these

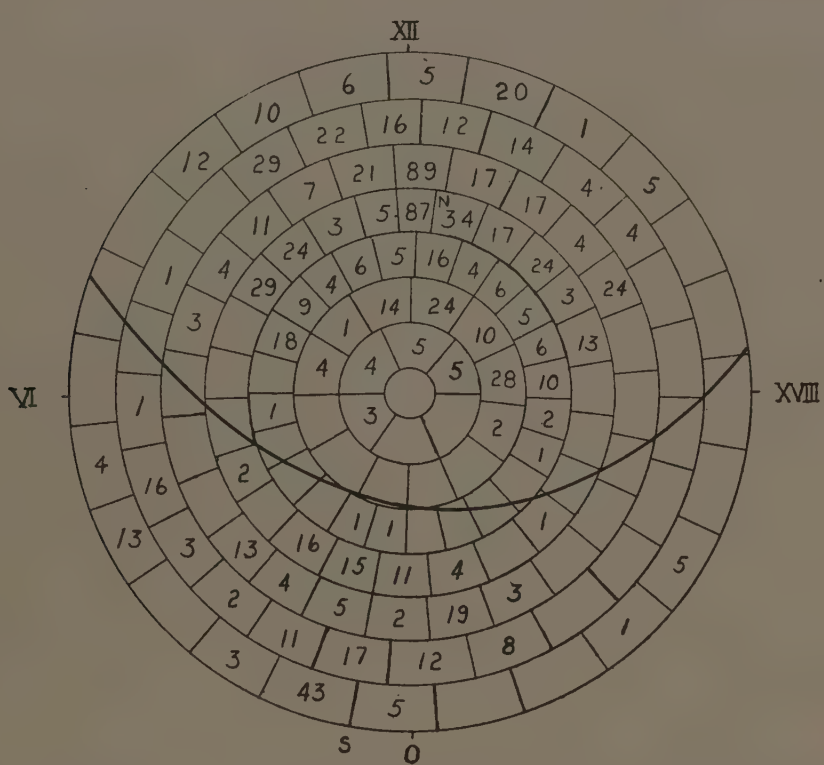


FIG. 187.—Distribution of nebulæ according to Fath. (*From plates taken at the Mt. Wilson Observatory.*)

small objects to be different in character from the larger ones which show the spiral structure, for these larger ones on small-scale plates look just like the small ones on large-scale plates. The assumption is therefore usually made that many at least of these numerous small objects are also spirals but either so far away or so small that it is not possible to bring out the spiral form by the means at present at our disposal. This assumption does not appear unreasonable and is made in what follows.

Figure 187 shows the distribution of these nebulæ as found by Fath on a series of 139 plates taken with the 60-inch reflector of the Mt. Wilson Observatory. These plates were evenly distributed over the sky at 15° intervals from the north celestial pole to declination −15°. The figure represents the sky from the north pole to 22°.5 south declination. The circles are 15° apart, so that any point half way between is at declination 75°, 60° . . . −15°. Right ascension is indicated along the circumference. The center of each area thus represents the position of a plate and the number within the area gives the number of nebulæ found on the corresponding plate. The north and south galactic poles are indicated by N and S respectively and the curved line shows the position of the Milky Way. It is evident that these nebulæ avoid the Milky Way and show a tendency to cluster around its poles, although this clustering is much more marked around the northern than around the southern galactic pole.

There is no satisfactory explanation of this lack of uniformity in distribution. It has been suggested that most of these nebulæ lie outside the sidereal system and that occulting matter near the plane of the Milky Way prevents our seeing them. For the present, it seems best to accept the apparent distribution as an observed fact and await further light on the subject.

425. The Number of Nebulæ.—No systematic effort has ever been made to solve this problem. It would require many years of work on the part of an observer with a large telescope, and at present there are more pressing problems requiring attention. The figures that have been published from time to time are estimates based on a limited number of plates taken for other purposes, and such results are therefore merely by-products obtained in the course of other investigations. Estimates of this character have been made by Keeler, Perrine, Fath, Curtis and Seares. Their figures are 120,000, 500,000 to 1,000,000, 262,000, over 1,000,000 and 300,000 respectively.

The difference in these estimates lies in the nature of the material used. In each case the method of treatment was the same. The nebulæ found on plates taken for other purposes were counted and the fraction of the sky covered by the plates determined. Then, on the assumption that plates covering the entire sky would show the same average number of nebulæ as those in hand, it was a simple arithmetical process to calculate the probable number that could be photographed with the same

exposures and plates in the entire sky. The average number of nebulæ would depend on the particular regions which had been photographed. Thus Wolf found 517 small nebulæ on a single plate in the region around N. G. C. 598 and Curtis photographed 249 nebulæ in an area 38′ by 39′ near the north galactic pole. A few plates with such large numbers of nebulæ would produce a high average, while, if a series of plates covered none of these exceedingly rich regions, the average number would be comparatively low. This seems to offer a reasonable explanation for the difference in the above estimates of number. It is the author's opinion that, for the present, the number of nebulæ within reach of the large photographic telescopes may be taken provisionally at from one-quarter to one-half a million.

426. Novæ in the Spirals.—In 1885, Hartwig discovered a faint nova in the Andromeda nebula. It rose to the seventh magnitude and then faded away to below seventeenth. Ten years later Mrs. Fleming found a similar object in N. G. C. 5253. These two cases did not excite more than the normal interest in faint novæ, for it was always a question whether the stars noted really belonged to these two nebulæ or whether they were merely observed in the same direction. In 1917 to 1920, however, observers of the Lick and Mt. Wilson observatories startled the astronomical world by reporting 17 novæ in the Andromeda nebulæ and this number has since increased to 46. This announcement stimulated the interest in this phase of investigation of the spirals, and novæ have since been found in at least four others and have been suspected in several more. None of these novæ have been bright enough to be visible to the naked eye. So far as can be determined, they have behaved like novæ in general, in that they appeared suddenly and then gradually faded away. There seems to be no reason for considering them as differing from the general run of novæ (Sec. 385) except that they have appeared in the midst of spirals instead of in the Milky Way.

427. Variable Stars in Spiral Nebulæ.—In 1924, Hubble of the Mt. Wilson Observatory announced the discovery of many variable stars in five spiral nebulæ, including the two largest, the Andromeda nebula and N. G. C. 598. Among these variable stars there were 12 Cepheids in the Andromeda nebula and 22 in N. G. C. 598. The periods of these Cepheids range from 17.6 to 50.2 days, and their magnitudes from about 18.3 to 19.4.

The Nature of the Spiral Nebulæ

428. Preliminary Considerations.—This problem is one of the most important before the astronomical world to-day. Here we have hundreds of thousands of objects in the sky which may have a spiral structure but, considering their number, we still know very little about them.

Before proceeding to a consideration of the factors involved in the problem we must utter a word of caution. Many who write upon this subject seem to assume that all spiral nebulæ are of approximately the same real dimensions and that the apparent variation in size is due to variation in distance. There is nothing in the nature of the case to warrant such an assumption and much that can be urged against it. Thus, it was stated in Sec. 425 that Wolf had found 517 small nebulæ near N. G. C. 598. He considers them to be in the continuation of the arms of the main spiral and, as they are mostly elliptical in outline, they are just as likely to be spiral themselves as the thousands of other objects of the same general size and form. Since they are almost certainly merely parts of the larger spiral, we seem to have good reason to hold that the spirals vary greatly in size. The author is inclined to believe that in time proof will be available to show that some spirals have dimensions at least 1000 times those of others and therefore probable masses in the ratio of 1000^3 to 1.

429. The Facts.—Let us now return to the problem and collect the observed facts. These can be summarized as follows: (1) There is not a single spiral nebula or suspected spiral for which a reliable trigonometric parallax has been determined. (2) A few spirals give evidence of very small proper motion. (3) The spectra of the central parts of the larger spirals, with few exceptions, are similar to the spectra of F-, G- or K-type stars. (4) At the same time that Hubble announced the discovery of Cepheid variables in the Andromeda nebula and N. G. C. 598, he also stated that he had succeeded in resolving photographically the outer portions of these nebulæ into myriads of stars apparently differing in no way from ordinary stars. (5) The radial velocities of the larger spirals range from -300 to $+2000$ km per second. (6) Within the limits of the Andromeda nebula 46 nova have been found in the space of 6 years and a few novæ have been found in other spirals. (7) Cepheid variables have been found in the

two largest spirals. (8) The spirals avoid the plane of the Milky Way and are most numerous near the galactic poles. (9) The spirals are in rotation.

430. Parallax.—The absence of a measurable parallax and the very small proper motion favor the view that such spirals as have been tested in this way are at very great distances. The tests, however, appear to have been applied only to the larger spirals, and it may be that when the smaller ones are investigated some of them will yield measurable trigonometric parallaxes, or at least proper motions from which distances can be inferred.

431. Spectra.—The spectra of only the central portions of the larger and brighter spirals have been investigated, because exposures of many hours' duration, 10 to 80, are necessary for all except two or three of the very brightest, even when using the most rapid photographic plates obtainable. The spectra thus obtained correspond to the spectra of stars of types F, G and K. The only known sources of such stellar-type spectra are stars and therefore the only simple explanation is that the spectra of these nebulæ are derived from stars. Two ways are possible: (1) A star or a few stars illuminate otherwise dark nebulous matter, which, in turn, reflects its light to us. (2) The brighter parts which can be investigated spectroscopically are themselves composed of stars.

If we accept the first possibility, we would expect to be able to see these stars since we can see the reflected light, but this cannot be done. The nuclei are not of stellar character, and even when there is a fairly well-defined nucleus it is but little brighter than the parts surrounding it. The possibility therefore must be abandoned until those who adhere to it can find the stars. Furthermore, if the light is reflected, we would expect some of it to show polarization, but Meyer could find no evidence of polarized light in four spiral nebulæ which he investigated.

The second possibility therefore is left. How are we to understand it? Some years ago the author obtained a spectrum of the Andromeda nebula with an exposure of 18 hours. The G-type spectrum obtained was the same, except for intensity, over a strip 5′ of arc in length. If this spectrum came from stars alone, then the stars must be widely separated, for the actual brightness of the area is not very great. But if the stars are widely separated, why were they not observed? The answer is that the entire group is so far away that individual stars could not be recognized

and what we have is a great mass of stars separated sufficiently to give the weak light per unit area but so far away that no telescope has shown them individually.

A further implication is also made. Since the spectrum is of G-type, most of the light must come from stars of approximately this type, and, if there are stars of other types present, they must be either relatively few or comparatively faint, so that the G-type stars predominate.

The question therefore arose whether such an assumption of dominant type is reasonable, and, if so, whether it would be possible to find clusters of stars which would act in the same way. To test the matter, several of the brighter globular clusters were investigated, and it was found that most of them gave affirmative results as stated in Sec. 410. It was therefore shown that great star clusters actually had stars in which, so far as intensity was concerned, one type was dominant. Accordingly, we come to the conclusion that the central parts of the spirals investigated, which alone are sufficiently bright to give results, are composed of myriads of stars.

432. The Novæ.—The discovery of so many novæ in the Andromeda nebula presents a further problem. In our sidereal system we have averaged about one nova a year in recent years. The Andromeda nebula has developed many more. From this fact it has been argued that possibly the star density in the nebula is greater than in our galactic system. Seares has investigated the brightness of our system as viewed from without and finds it would not appear nearly so bright, area for area, as the brighter nebulæ. If these nebulæ are themselves sidereal systems their star density must be much higher than ours. The number of novæ in the Andromeda nebula favors this point of view.

Lundmark has made an investigation of the Andromeda nebula on the basis of the novæ. On the assumption that these novæ are of the same absolute magnitude as those of the Milky Way whose absolute magnitudes are known, it was found that the parallax of this nebula is $0''.0000015$. This corresponds to a distance of 600,000 parsecs, or about 2,000,000 light-years. The diameter, accordingly would be 60,000 light-years.

433. Variable Stars.—Since Hubble has discovered Cepheid variables in the Andromeda nebula and in N. G. C. 598, the problem of the distance of these two objects may be considered fairly well settled, for it was possible to apply the Leavitt-Shapley

law, as in the globular clusters. The results obtained by this method give distances of 285,000 parsecs, or 930,000 light-years.

434. Radial Velocities.—Another point to be considered is the extraordinarily high radial velocity of the larger spirals. The values, averaging +600 km per second, seem to place them in a class quite different from the objects we have to deal with in our sidereal system, where the average velocity of the stars with respect to the sun is of the order of 20 km per second and the relative velocity of Kapteyn's two star drifts is 40 km per second.

435. Rotation.—Van Maanen's values of the rotation periods for some of the larger spirals point to relatively small dimensions and masses of these objects as compared with our stellar system.

If we take the rotation period of the outer portions of N. G. C. 598 as 160,000 years, then a simple calculation shows that a point in this portion will move 0.022 times its distance from us in this period (diameter of nebula about 25′). Taking Hubble's value for the distance, this gives a linear velocity of 40,000 km per second, a velocity which does not seem possible.

436. Location.—The fact that the spiral nebulæ appear to avoid the plane of the Milky Way does not seem to have any direct bearing on the problem of their nature, and therefore will not be discussed further.

437. Summary.—The interpretation of these results is difficult and astronomers are divided in their opinions. It must also be remembered that, because of the difficulty of the problem, only a comparatively small number of spiral nebulæ have been investigated and these are the largest and brightest.

Two opinions predominate. The first is that the spirals, while large objects, are still small when compared with the dimensions of our sidereal system and are at distances comparable with those of the globular star clusters. The second is that the larger spirals are sidereal systems, comparable in size with our own, and at distances of the order of a million light-years or more. This second theory is usually called the "island universe" theory.

At the present time it seems that, among those qualified to express an opinion, the majority favor the "island universe" theory. This theory grips the imagination and is of profound interest to many who otherwise give but little attention to astronomy.

Let us tabulate the favorable points used by the adherents of each theory, those in column 1 being in favor of the "island universe" theory, that in column 2 being opposed to it.

1	2
No direct values of parallax.	Van Maanen's rotation values
Very small or no proper motions.	
High radial velocities.	
Novæ in spirals.	
Cepheid variables in spirals.	
Spectra.	
Resolution of outer parts of two largest spirals into stars.	

438. Changes in Nebulæ.—The appearance of novæ and variable stars in some of the spiral nebulæ has been noted (Secs. 426–427). Barnard observed variations in brightness in the nucleus of the planetary nebula, N. G. C. 7662, and the central star of the ring nebula in Lyra is likewise known to vary. Until

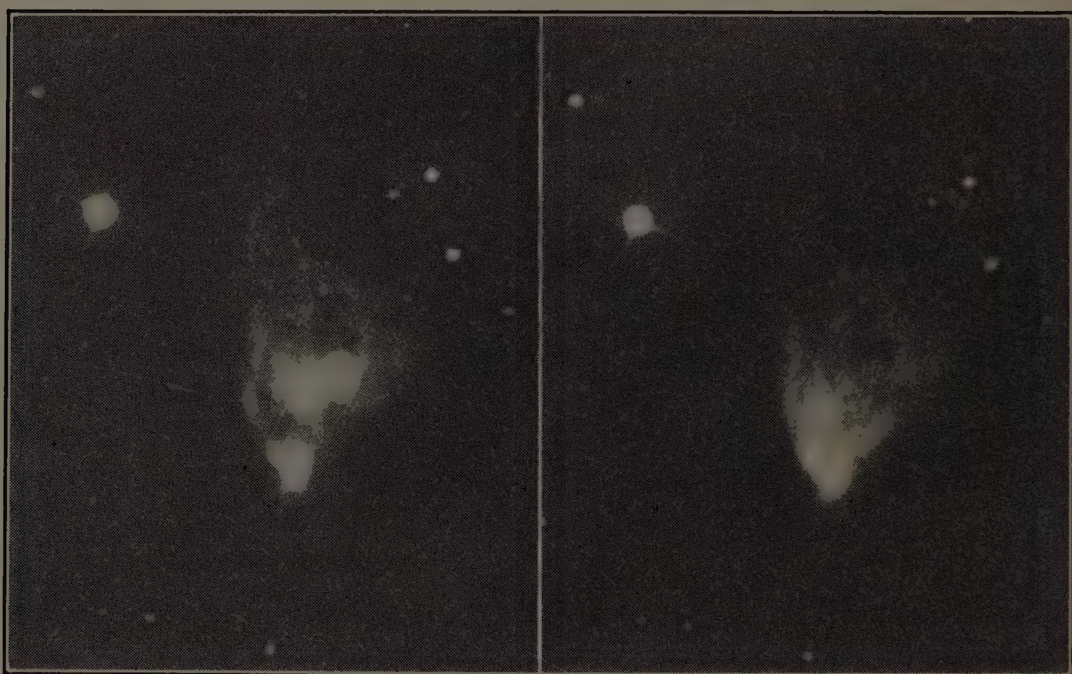


FIG. 188.—Hubble's variable nebula, N. G. C. 2261, in Monoceros. (*Photographed at the Mt. Wilson Observatory, Sept.* 18, 1920 and *Nov.* 1, 1921.)

1918, a few instances of change were also known in other nebulæ. In these instances, the nebula appears in the vicinity of, or connected with, a variable star. In one of these nebulæ, N. G. C. 2261, whose variability was discovered by Hubble, Slipher has shown that its spectrum is just like that of the variable star with which it is connected, so that we may assume it to be shining by reflected starlight like the Pleiades nebulæ. The variation in the brightness of the nebula, however, seems to have

no direct connection with the variation of the star. The changes in the nebula are therefore not due merely to variations in the brightness of the star. Figure 188 is a reproduction of two photographs of this nebula. It is very evident that marked changes in brightness have occurred in different parts. Changes have been noted in photographs taken only 24 hours apart.

In 1918, Lampland announced that a comparison of Mt. Wilson and Lowell Observatory photographs of N. G. C. 6992 showed some changes in the nebulous filaments of this object. Three years later changes were also noted in the "Crab" nebula, N. G. C. 1952, and in the form and structure of the nucleus of the spiral nebula N. G. C. 4254. It therefore seems probable that before many years it will be possible to compare photographs taken a few years hence with the many fine ones obtained at various observatories from about 1900 to 1910, when the first good large-scale photographs were made, and get a reasonable knowledge of changes that must be occurring in all the prominent nebulæ.

439. Absorption of Light in Space.—The various investigations dealing with star ratios, the Leavitt-Shapley law, etc., all involve the assumption that there is no loss of light in interstellar space. The dark nebulæ in certain regions show clearly that they cut off light from possible objects beyond them and the question of whether there is thinly dispersed matter throughout space which will either occult or scatter starlight is of the greatest importance in all investigations on the structure of the universe.

A gas such as the earth's atmosphere exerts a particular effect on light waves of various colors which can be measured. Red light will travel faster in it than yellow and yellow faster than blue light. If space is more or less filled with a tenuous gas, we might therefore expect to test the matter as follows:

Suppose we observe a variable star, separating its light into a yellow and a blue portion. If yellow light travels through space more rapidly than blue light, then the star would show a maximum or minimum by its yellow light earlier than by its blue light. No such effect has been definitely established. In the case of 12 variable stars in the cluster N. G. C. 5904, Shapley found no certain difference, although the cluster is at a distance of 40,000 light-years. Other tests also point in the same direction. We may conclude therefore that, in general, there is no appreciable amount of gaseous matter in space which will retard light of short

as against long wave-lengths, and hence no gaseous matter which will either absorb or scatter light in appreciable amounts.

Another possibility, however, is presented if we think of larger particles of matter comparable in size with grains of sand or larger. Such particles would serve to absorb and occult light of practically all wave-lengths and thus weaken the total light received. While we must reckon with the possibility of such material, we have no evidence either of its existence or of its absence. We are therefore compelled to wait for further evidence before it is possible to reach any conclusion on this point.

CHAPTER XVIII

THE STRUCTURE OF THE VISIBLE UNIVERSE

440. Nature of the Problem.—In considering the relationship between the various units which have been studied thus far, we are approaching one of the great, if not the greatest of astronomical problems. We shall have to attempt to determine the relative importance of stars, star clusters and nebulæ of various kinds, as well as their relations and positions with respect to one another. A complete solution of the problem is not possible. In some instances there is a marked difference of opinion concerning the interpretation of data, but certain general ideas concerning the problem as a whole are gradually emerging and it is these we shall attempt to portray briefly.

441. The Milky Way System.—In Chap. XVI we learned that by averaging the results of star counts there was evidence that the stars of the Milky Way were confined in a space shaped somewhat like a thin watch or lens. The results obtained by Kapteyn from material available in 1921 to 1922 indicated that the watch-shaped space had a diameter of approximately 17,000 parsecs and a thickness of 3400 parsecs. The star counts of Seares and van Rhijn will show the same general shape but considerably greater dimensions.

In these star counts no discrimination has been made between north and south galactic latitudes, and the values for the galactic longitudes have been averaged through the entire circuit of 360°. In consequence, while the general shape may be determined, it is not yet possible to determine much of anything in regard to the details of structure.

442. Star Clustering.—A study of the photographs of the Milky Way shows that the stars are not uniformly distributed but have a clustering tendency. This is also shown by the many clusters near the sun, such as the Pleiades, Hyades and others. Besides these, we have the globular clusters. All stars are not necessarily members of clusters of one sort or another, but the cluster grouping is a marked characteristic of most of them.

443. Easton's Theory.—Some years ago Easton published a theory that the Milky Way system of stars is a great spiral structure, in some ways resembling a spiral nebula like N. G. C. 598. On this theory the star clouds of the Milky Way correspond to the coarser details of the nebula and the parts of the galaxy from Cygnus to Scorpio to the two arms of the spiral, one being near and the other much farther away. Easton assumes the center of the spiral to be in the direction of Cygnus and the sun placed at the point S (Fig. 189).

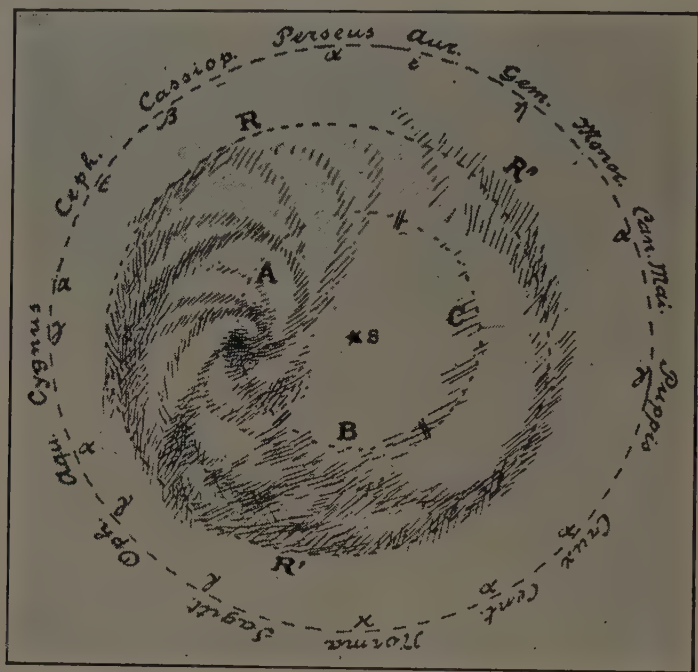


FIG. 189.—Easton's theory of the sidereal system. (*Courtesy of the Astrophysical Journal.*)

This theory has a number of points in its favor, as it allows for the clustering of the stars, the general appearance of the Milky Way, the main boundary as indicated by the results of star counts, star drifts owing to interpenetration of the members of adjacent clusters, etc. At the present time it does not appear safe to accept Easton's theory without reservation, but it is the best one available which attempts to organize the stars into a dynamical system.

444. Shapley's Theory of the Milky Way.—Shapley considers the stars in general as still largely in cluster formation, these clusters being located in the watch-shaped space and at least partially intermingled. He estimates the diameter to be from 200,000 to 300,000 light-years and the thickness from 5000 to

10,000 light-years. Near the surface as well as outside the "watch" the globular clusters are scattered. Of the 18 globular clusters whose radial velocities have been measured, about one-half are approaching and the other half receding from the Milky Way system. Shapley holds that these clusters, under the gravitative control of the larger system, vibrate back and forth through the galaxy, losing some of their stars to the main group at each passage until all will be absorbed. He assumes the center of the entire system to be in the direction of the constellation Sagittarius at a distance of about 60,000 light-years from the sun.

Thus far Shapley has not accepted the Easton theory of general structure but has offered no other. The enormous dimensions he assumes for the system have not been universally accepted, but if we grant that the distances derived for the globular clusters are of the right order, then the observations by Barnard that some of these can be seen against a background of Milky Way stars require dimensions of the order given.

445. Relation of Gaseous and Dark Nebulæ to the Galactic System.—The distances obtained for the planetary nebulæ show clearly that they belong within the boundaries of the galactic system. The distance of the Great Nebula of Orion, 200 parsecs, determined indirectly from the proper motions of stars enmeshed in it, makes it a near neighbor of the sun. Many of the nebulæ, both the gaseous "bright-line" and the dark ones whose distances have not been measured, are associated so closely with the star clouds of the Milky Way that it seems reasonable to conclude that the known examples of these two classes of nebulæ are almost wholly within our stellar system.

446. Relation of the Spiral Nebulæ to the Galactic System. The work of Lundmark on the novæ of the Andromeda nebula, and, more especially, Hubble's results from the Cepheid variables of the same nebula and of N. G. C. 598, make it practically certain that these two objects at least are outside the galactic system, even if we accept Shapley's figures for the dimensions of the latter. The fact that both their spectra and the resolution of their outer parts show them to be stellar systems of great size seems an argument in favor of Easton's theory of the galactic system, and it is probable that when we see these objects we are looking at stellar systems which in form are more or less like our own.

Seares' study of the apparent surface brightness of our stellar system, if viewed from without, showed that its brightness, area for area, is much less than that of the Andromeda nebula. This may be due to a greater star density in the latter, to brighter stars or to a combination of the two. Our stellar system may therefore be a faint though large spiral nebula.

When we consider the many other known spirals (about 500) and the many thousands of probable ones, it is a most important question whether we are to consider them all in the same class as the Andromeda nebula and N. G. C. 598 or not. The spectra of the central parts of the brighter ones agree with those of the two mentioned. So far as our very limited evidence goes, we may say that some of the other spirals are probably stellar systems as well. Until we know more about the subject, however, we cannot be certain whether small spirals only appear so because of great distance or whether they are in reality small when compared with the larger examples known. The author hazards the guess that small spirals will eventually be found.

447. Summary.—Essentially all the stars within reach of our present telescopes as well as the planetary, diffuse and dark nebulæ belong to one stellar system, the galactic system. This system, according to Shapley, has a thickness of about 10,000 light-years and a diameter of possibly 300,000 light-years. It may have the general structure of a spiral nebula. Gravitationally connected with this system are the globular star clusters, most of them at present outside the boundaries given, some approaching and some receding.

Beyond this system there are at least two other stellar systems, the Andromeda nebula and N. G. C. 598, distant about 1,000,000 light-years from it. Besides these two there may be many others, but the evidence is not yet sufficient to warrant a definite assertion.

CHAPTER XIX

COSMOGONY—A STUDY OF ORIGINS

The human mind is limited in perception and experience and it is conceivable that in spite of our best efforts we shall never fathom the history of the universe. Nevertheless, our experience has shown that progress is not impossible and it is this which inspires the scientific worker to gather facts, to study them in the hope of finding the underlying law and to formulate hypotheses which are to be tested by experiment and observation.

448. The workers in the physical sciences attempt to study the physical universe. They recognize that they work in a limited field and that physical truth is not the whole of truth. They leave to philosophy and religion the search for the absolute and the explanation of the purpose of all things.

In any scientific consideration of the origin and development of a celestial body or structure one fundamental hypothesis underlies all thinking, namely, *the universe is an orderly universe.* This implies that the laws now governing the universe were in operation in the past and are universal in their application. Some of these laws are the law of gravitation, the conservation of matter and energy[1] and that every effect has an adequate cause.

The various theories which we shall consider are not to be thought of as dogmatic statements of ultimate truth, but as suggestions put forward to guide mankind in the search for truth. Their authors were or are men who would willingly abandon their theories as soon as their untenability could be shown and who earnestly search for errors in their own theories.

The theories which we shall consider are those relating to the origin and development of spiral nebulæ, stars and the solar system. In no case is there an attempt to account for the origin of matter and energy or the laws governing them. These problems for the present lie beyond the realm of science.

[1] In view of the modern conception of matter as a form of energy this law may be stated as follows: The sum of matter and energy in the universe is constant.

THE ORIGIN OF SPIRAL NEBULÆ

449. Jeans' Theory.—As set forth by Jeans in his Halley Lecture in 1922, this theory is as follows:

Assuming the existence of a gaseous mass, some millions of times the mass of the sun, which is in slow rotation and contracting under its own gravitation, the theory attempts to follow its subsequent history.

At first the form will be that of an oblate spheroid with the shortest axis as the rotation axis. At a certain critical rotation period the equatorial bulge becomes a sharp edge, so that the mass as a whole has the shape of a double-convex lens. At the edge centrifugal force and gravitational force just balance. Owing to the tidal action of other masses in the universe, the matter at the edge will not be left as a ring but at two opposite points filaments of gas will be given off, the beginning of two arms of the spiral. Continued shrinkage and increased rotational velocity of the nucleus will continue this process of providing the material for the two arms until but little is left in the nucleus. In the meantime, however, the material in the arms is not in equilibrium and these will break up into units of greater or less size, the mean mass of a unit being that of an average star, about 10^{34} grams (10^{28} tons).

The next step will be to follow one of the condensations in its further developments.

THE EVOLUTION OF A STAR

450. Lockyer's Theory.—The connection between spectral type and temperature of the stars (Sec. 344) was a temptation to think that, since stars would cool off with advancing age, the B stars were the youngest and the M stars the oldest of the series. One difficulty, however, lay in the way, namely, to account for the enormous temperatures of the so-called earliest stars in any simple way.

Many years ago Sir Norman Lockyer of England had proposed the theory that stars should first increase and then decrease in temperature and had named certain characteristics by which he thought it possible to distinguish between those of rising and those of falling temperature. His theory, however, was not favorably received because of certain assumptions he found it necessary to make.

451. Russell's Theory—About 1912, Russell of Princeton announced a theory which commanded almost instant attention, as it was based on more simple assumptions, and recent discoveries have gone far to confirm it. Briefly stated, the theory is as follows:

The matter from which a star is made is at first a mass of gas which is gradually drawn together by the mutual gravitation of its parts. When the mass is dense enough to produce appreciable pressure, the temperature begins to rise. As time goes on the mass becomes denser and hotter until it is of a sufficiently high temperature to shine as a star of M type. At the time this temperature is reached, the mean density is still very low and the new star is therefore of great size, a "giant." As the density increases still further, the temperature also rises, according to Lane's law, and a K-type giant results. The process continuing,

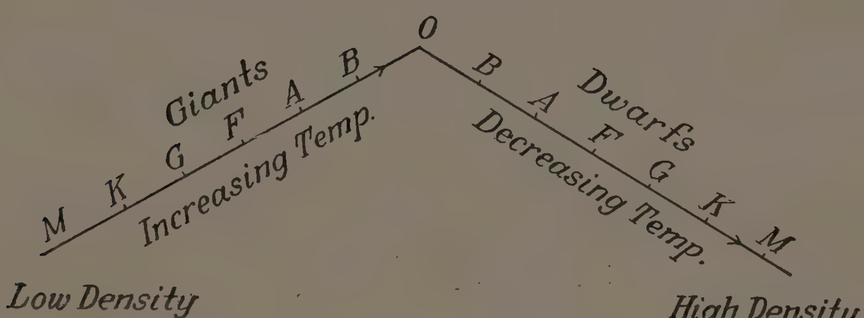


FIG. 190.—Representation of Russell's theory of stellar evolution in its original form.

the star gradually grows denser and hotter and its spectrum changes to G, F, A and finally, when hottest, to B type. By this time, however, the density becomes so great that radiation equals the amount of heat developed by contraction and finally exceeds it. The star then begins to cool and shrink, the spectrum becoming, in turn, of A, F, G, K and M type. As the dimensions are now much smaller, it is a "dwarf" star.

Figure 190 shows this theory diagrammatically. Such a development, however, would be possible only for stars of the largest mass. For a star of smaller mass there would not be sufficient gravitative effect to produce high pressures and correspondingly high temperatures, so that it might rise only to some intermediate spectral class as a maximum before beginning to cool.

Very recently, J. S. and H. H. Plaskett have shown that the average O-type stars are both hotter (15,000 to 22,000°) and more massive than any other class of stars, and suggest that they should stand at the apex of the evolutionary scheme instead of the B-type stars. Fig. 190 has been modified accordingly.

The terms *giant* and *dwarf* as applied to a star mean not so much difference in mass as difference in size. For any one star the mass will remain practically constant throughout its life history, but its diameter will vary greatly. Thus during early life it will be a giant and after reaching its maximum temperature gradually change into a dwarf. According to Russell's theory, the sun has passed the maximum and is a G-type dwarf.

452. Evidence.—Russell's theory seems a reasonable explanation of the changes a star might be expected to go through in the course of its history and is in accordance with many observed facts. Some of these will be enumerated.

1. Hertzsprung showed some years ago that some stars are evidently very much larger and brighter than others of about the same spectral type. We owe the use of the terms *giant* and *dwarf* to him.

2. Careful examination of the spectra of the stars shows that in the giants some lines are of different intensity as compared with the same lines in similar spectra of the dwarfs.

3. The existence of giant stars has been proved by the actual measurement of the diameters of a few stars.

4. Investigation of the masses of double stars by Ludendorff and by Seares have shown that the mass decreases as the type changes from O downward in the spectral scale.

5. According to the theory, giant stars have great dimensions and therefore an M-type giant would have such a vast surface that even though comparatively cool it would have great luminosity. Decreasing diameter in the giants would be accompanied by increase in temperature, which would counteract the effect of less radiating surface. The theory therefore requires the giants, as a class, to be stars of relatively great absolute magnitude. Such stars are found with spectra ranging from M to B types.

453. Eddington's Researches.—One of the most important contributions ever made to the theory of stellar evolution was Eddington's work on the "Radiative Equilibrium of the Stars" in 1916 and 1917. In these papers he has shown that a star of

mass a little less than one-seventh the sun's mass would be able to reach a maximum temperature of only 3000°, while a star very much more massive than the sun would develop such a high temperature that it would have to separate into two or more parts. To use specific values, and stating the case in somewhat arbitrary fashion, we might say that a star whose mass is one-tenth that of the sun would never become a self-luminous body, although it might possibly exist as a dark star, while one whose mass was 100 times that of the sun either could not form at all or would be broken up because the disruptive forces due to the high temperatures developed would exceed its gravitational force. Luminous stars are therefore limited in mass to a range from about one-tenth to 100 times that of the sun.

This theoretical investigation of Eddington's is in accord with observation, for the star of least mass known, the companion of Krueger 60, has a mass of one-fifth that of the sun, according to Aitken, while that of greatest mass, B. D. +6° 1309, is a double star with components approximately 86 and 72 times the sun's mass. The latter was discovered by Plaskett in 1922.

In 1924, Eddington published another paper which was quite revolutionary. He assumes that the radiation of a star has its source in the destruction of the atoms, so that it would diminish in mass with increasing age. He further assumes that the intense heat in the interior of a star has both stripped the atom of most of its electrons and broken up the nuclei of the heavier atoms if such exist there. This permits enormously greater condensation before the atomic nuclei, and nuclei with less than the normal number of electrons, seriously interfere with continued contraction, so that a density up to 50,000 or more on the water standard is possible. The companion of Sirius may be of this great density.[1] Should these views ultimately be verified, it is evident that Russell's theory (Sec. 451) will have to be modified.

[1] It is evident that a mass of this density would have an enormous surface gravity. Einstein predicted that a radiating atom in an intense gravitational field would have its vibration frequency reduced so that the wavelength of the particular radiation would be increased. In 1925, Adams announced a shift of +0.32 A for the hydrogen lines in the spectrum of the companion of Sirius. This value, on the Einstein hypothesis, would give a radius of 18,000 km, a density of 64,000 and a surface gravity nearly 40,000 times that at the earth's surface for this extraordinary star.

Russell has recently proposed a change of his original theory on the assumption that the principal source of heat of the stars lies in the disintegration of matter within the body of the star. He assumes that the central temperature of the giant stars is below 30,000,000° and that some of the matter they contain can be transformed into energy at this lower temperature. As the central temperature slowly rises to the standard of 30,000,000°, the stars gradually reach the top of the series, as shown in Fig. 190, and then follow the descending side, all the time diminishing in mass because of their radiation. When near the end of this sequence and with the internal temperature still rising, the more refractory atoms are disintegrated and at the same time those remaining have lost many of their outer electrons, so that the enormous density of stars like the companion of Sirius is reached.

THE ORIGIN OF THE SOLAR SYSTEM

454. From time to time efforts have been made to analyze the present conditions in the solar system in order to attempt to read its past history. About the middle of the eighteenth century Wright of England, Kant of Germany and Buffon of France made such attempts and in one way or another contributed ideas toward the solution of the problem. At the present time, however, there are only two theories which, with modifications, are attracting any attention in the scientific world, namely, the Nebular Hypothesis of Laplace, which was published in 1796, and the Planetesimal Hypothesis of Chamberlin and Moulton, which was developed in the early years of the present century.

Before taking up these two theories we shall find it desirable to consider the present facts which any theory should explain. The principal ones are as follows:

1. The peculiar law of rotation of the sun.
2. The revolution of all the planets about the sun in the same direction as the sun rotates.
3. The orbit planes of the principal planets are nearly coincident with the plane of the sun's equator.
4. The rotations of the planets, in so far as they have been certainly determined, are in the same direction as their revolution.
5. The satellites of the planets with few exceptions revolve around their primaries in the same direction as their primaries rotate on their axes.

455. Laplace's Nebular Hypothesis.—Laplace assumed that in the distant past all the matter in the sun and planets was in the form of a hot, rotating mass of gas extending out beyond the outermost planet. As this mass gradually contracted under its own gravitation, it rotated more and more rapidly until at its equator gravity and centrifugal force were exactly balanced. As the general mass continued to contract, the material at the equator would be left behind in the form of a flat ring analogous to the ring of Saturn. With continued contraction another ring would be formed in a similar manner as the first until finally the central mass became our sun and rings had been formed which were spaced approximately as the planets are now.

For a time after its formation a ring would continue to revolve about the central mass and then gradually condense into a single body, a planet. The planet, in turn, would continue to shrink and, because of rotation, leave behind one or more rings which, in turn, became its satellites.

This theory for many years was generally accepted as giving a reasonable explanation of the mechanical development of our solar system, and with, certain modifications, is still accepted by some scientists.

One of the difficulties of the theory is the intermittent action in ring development. It is difficult to see why, when once the process began, it should not be continuous, matter at the equator being continuously left behind as the central mass contracted.

Another difficulty is the assumption that a hot gaseous ring would not disintegrate. It would seem more than likely that the individual molecules, no longer under gravitative control, would, because of their molecular motion, fly off into space and be lost altogether.

Other objections have also been brought forward against the theory and most scientists have abandoned it entirely on the ground that it is inadequate both in its original form and also in the modified forms that have been proposed from time to time.

The second theory is the joint work of Professors Chamberlin and Moulton of the University of Chicago, and we shall consider it under the name given it by its authors.

456. The Planetesimal Hypothesis.—According to this theory our sun, at one time in the distant past, was a star of the ordinary kind without attendant planets and in a condition much as it is to-day. In its movements through space it approached another

star sufficiently close so that the latter raised huge tides within the body of our sun. These tides, combined with the great disruptive forces within the sun, as evidenced by the eruptive prominences still occurring, caused enormous prominences to be projected from it, not only in the direction of the second star but also on the opposite side. As the two stars swung round their common center of gravity, the eruptions continued for a time, but at any instant the line of eruption was in the line joining the two stars, on the one side toward the second star and on the other side away from it. The final result of the encounter for our sun was that, while on the whole it remained much as it was before, yet it was now attended by the matter thrown out in the prominences, the whole looking like a spiral nebula. Figure 191, which is taken

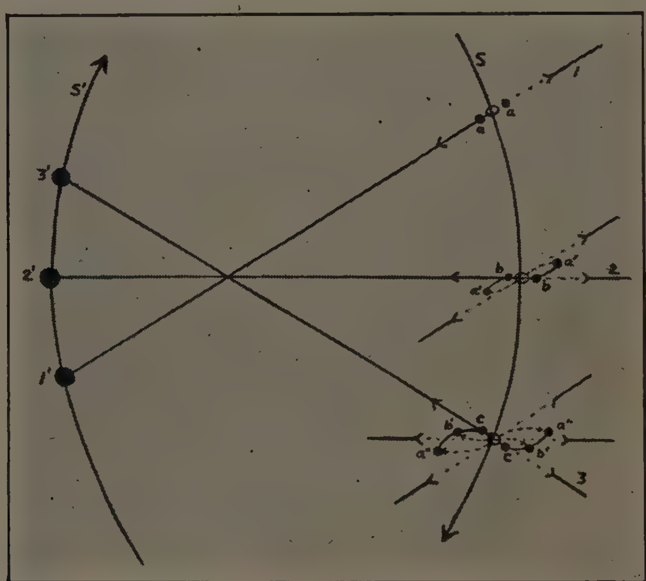


Fig. 191.—Partial disruption of sun caused by close approach of another sun. (*According to Chamberlin and Moulton. Courtesy of University of Chicago Press.*)

by permission from Chamberlin's "The Origin of the Earth," illustrates the process for three instants of time during the encounter.

In this figure let S represent the path of the sun and S' the path of the other star. When the two bodies were at 1 and 1′ respectively, the two prominences a and a would be thrown out. When the two suns had reached 2 and 2′, the original parts of the eruption would be at a' and a', while the parts just then being thrown out would be at b and b. By the time the suns had reached 3 and 3′ the former portions a and b would be at a'' and b' and the parts just leaving the sun would be at the points c. The

process is to be considered as more or less continuous, so that the parts *a*, *b* and *c* represent those portions of the entire prominences erupted at times 1, 2 and 3. A line drawn through these portions will be curved, so that the final form would be that of a small spiral nebula.

It is possible that some parts of the prominences might have been projected with such velocities that they were driven beyond the gravitative control of the sun and were therefore lost to it. The remainder would remain under the control of the sun. Some of these might plunge back into the sun and affect its rotation, while the remainder would revolve about it in orbits of various eccentricities. We are directly concerned only with the last group.

It is not at all likely that the prominences would be homogeneous throughout, and consequently there would be centers where the material would be more dense than elsewhere. These portions would not only contract under their own gravitation but would also draw in the less organized material in their vicinity. In the meantime, since the material nearer the sun would be revolving around it more rapidly than that farther away, the spiral arms would wind about the sun more and more so that they would become quite intimately mingled.

Thus, in time, the larger nuclei, by their attraction, would gradually clear up most of the matter in the vicinity of their orbits and if another smaller nucleus were to approach close enough, it would either be drawn in or become a satellite.

The foregoing is a brief statement of the main points of the theory which has been worked out in considerable detail. To follow it further, reference must be made to various publications of its authors. Mathematically, it appears to be a solution of the problem of the origin of the solar system, but whether it actually fits the facts seems to be a point on which there still exists a difference of opinion.

If we assume the correctness of the planetesimal hypothesis, it is possible to explain the probable origin of comets and meteors. These bodies may be considered as portions of the ejected material which revolved about the sun in highly elliptic orbits and which was in the immediate vicinity of larger masses so little of the time that it has not yet been entirely absorbed by them.

457. Modifications of the Planetesimal Hypothesis.—The essentially new point of view of the Planetesimal Hypothesis as compared with Laplace's Nebular Hypothesis is that two bodies

were involved in the genesis of the solar system instead of one. The details of the encounter depend upon assumptions as to the relative masses of the two, their dimensions and the closeness of approach.

Chamberlin and Moulton assume that the sun before the encounter was approximately as it is now, that most of the materials shot out cooled and solidified rapidly and that the planets and satellites were built up by the aggregation of these masses after solidification, the earth nucleus in particular remaining cold and adding but slowly to its mass.

Jeans, in his "Problems of Cosmogony and Stellar Dynamics," holds that our sun must have been expanded to the diameter of Neptune's orbit, and hence of very low mean density, at the time of the encounter and that only one long prominence was shot out on each side, the two prominences later breaking up into various parts. He also suggests that a large proportion of the satellites may have been formed by tidal disruption of the primaries while their orbits were highly eccentric.

Jeffreys does not find a greatly distended sun desirable and places the maximum diameter at the time of the encounter at 42,000,000 km, a value less than the diameter of Mercury's orbit. He agrees with Jeans that many of the satellites were probably formed by tidal disruption of their primaries but holds that the earth-moon system was not so formed. He also suggests that the prominence on the side opposite the disturbing body either did not form at all, or, if it formed, that it probably fell back into the sun.

Barrell follows Chamberlin and Moulton in the main but holds that the geologic evidence requires a fairly rapid fall of planetesimals of a size up to several hundred miles in diameter which, by their impacts, heated the earth until it became a molten mass. Schuchert agrees with Barrell that the geologic evidence favors a molten earth.

458. Conclusion.—It is evident, from the material in this chapter, that there is at present no generally accepted theory as to the origin of the solar system. Laplace's theory has few adherents outside of France. The planetesimal hypothesis, with possible modifications, is the only one accepted by any reasonably large group of thinkers. The problem is a very complicated one and its solution depends upon our ability to read the past out of conditions now existing. We believe the

problem not insolvable, but it may take many years before mankind acquires the knowledge and the skill necessary for its solution.

The larger questions involving the structure and history of the universe are still farther from solution. It may be that the theories now emerging as working hypotheses are evidences of our ignorance rather than of our knowledge. We do not know whether the universe is a mechanism which is using a limited store of available energy and which will eventually run down, or whether the dissipated energy of the stars is collecting somewhere in space and is to be used again.

The idea of an eternal material universe, forever changing but never reaching stagnation, is a philosophical conception which has a strong appeal to many minds, but the desire for such a condition is not a proof of its reality. The possibility of a cyclical process involving the entire universe of matter and energy must be granted, but we have not, as yet, any definite evidence upon which to base an opinion.

"The subject is new, and we must attend to observations, *and be guided by them*, before we form general opinions" (Sir William Herschel).

APPENDIX

In designating the stars of the constellations the letters of the Greek Alphabet are used and are given here for convenience of reference.

GREEK ALPHABET

α Alpha	ν Nu
β Beta	ξ Xi
γ Gamma	ο Om′-icron
δ Delta	π Pi
ε Eps′-ilon	ρ Rho
ζ Zeta	σ Sigma
η Eta	τ Tau
θ Theta	υ U′-psilon
ι Iota	φ Phi
κ Kappa	χ Chi
λ Lambda	ψ Psi
μ Mu	ω O′-mega

INDEX OF NAMES

H

I

J

K

L

M

N

O

P

R

S

T

U

V

W

Y

Z

SUBJECT INDEX

T

U

225